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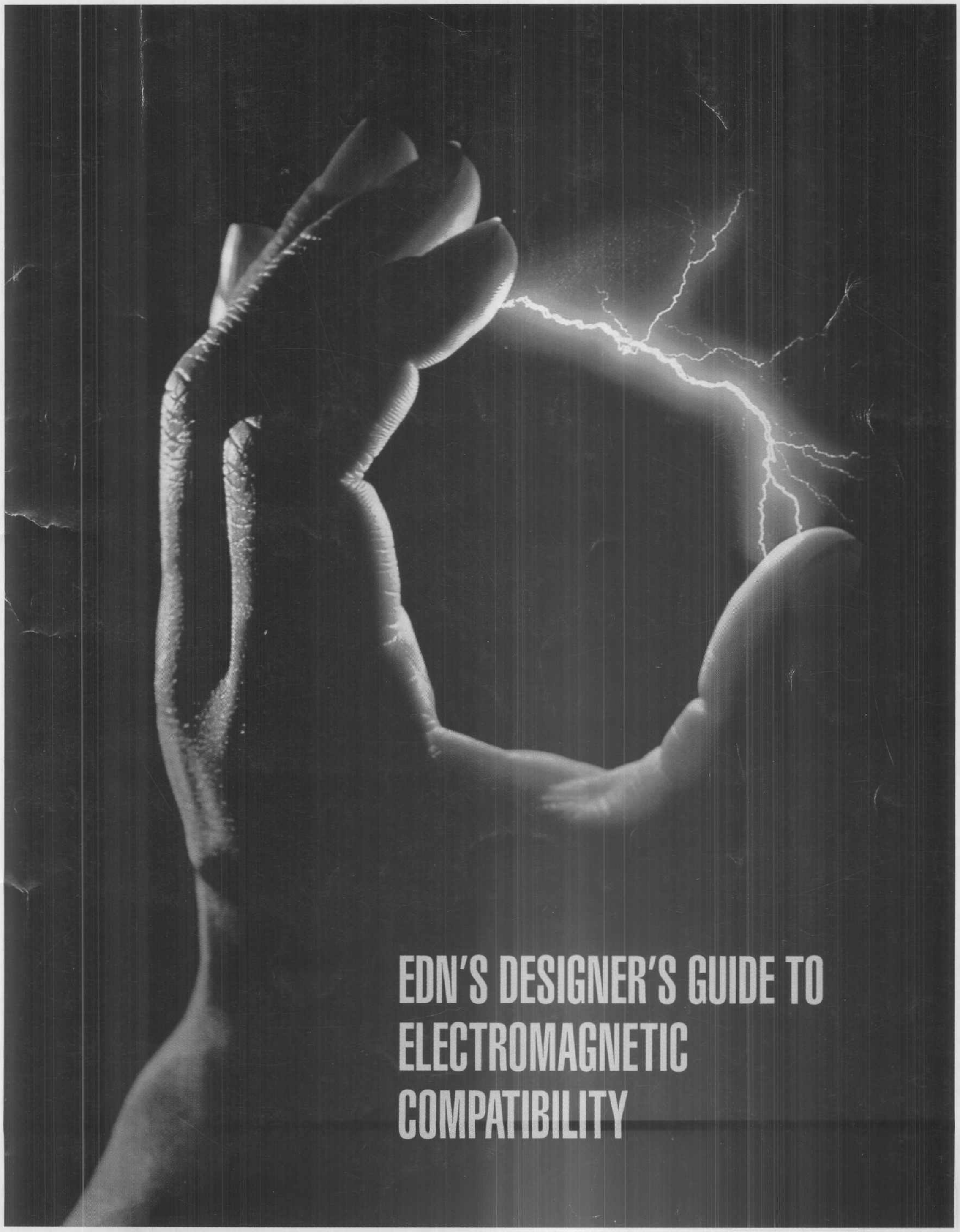

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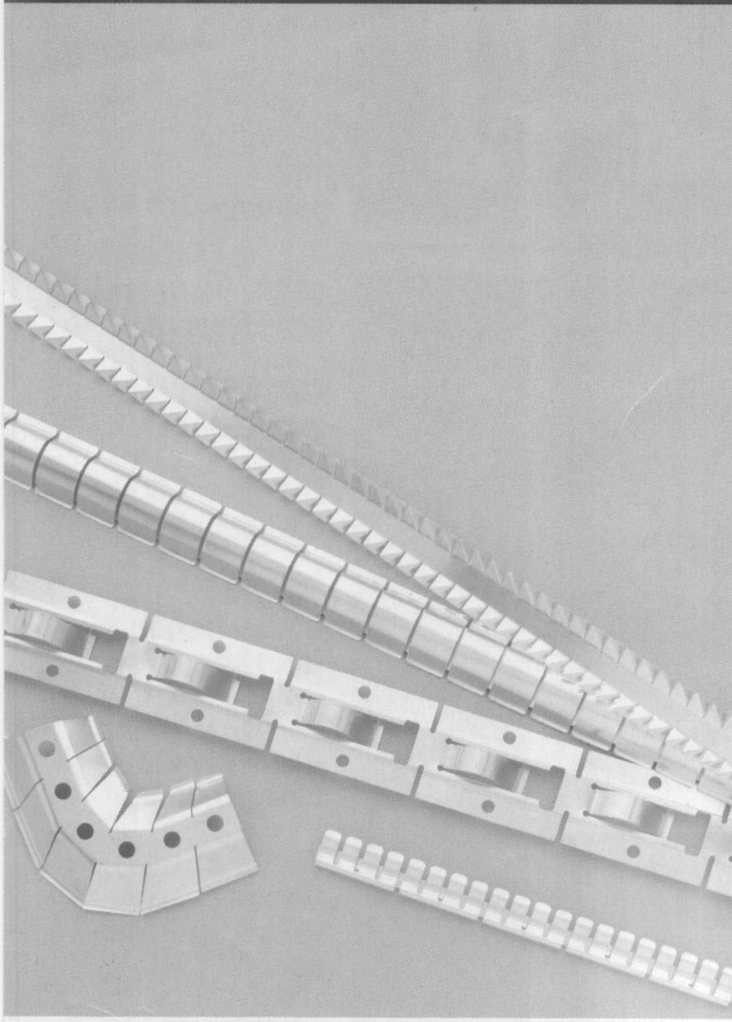

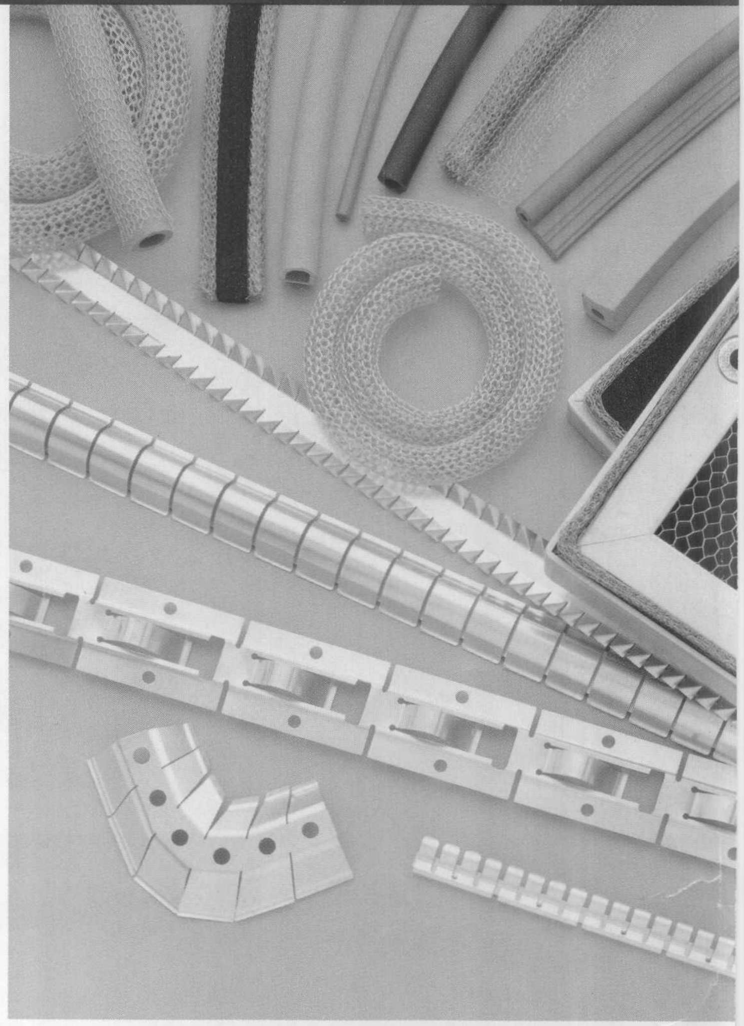

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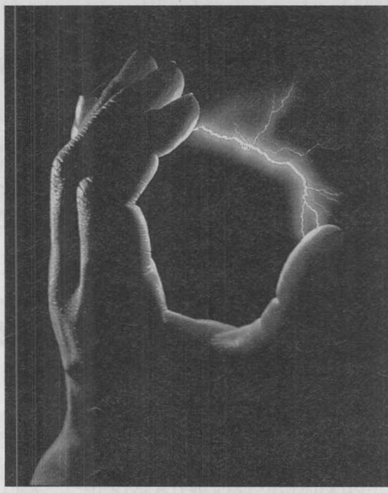

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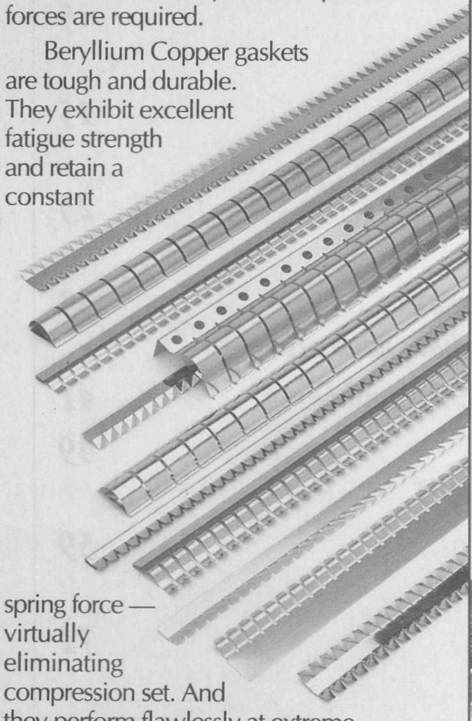
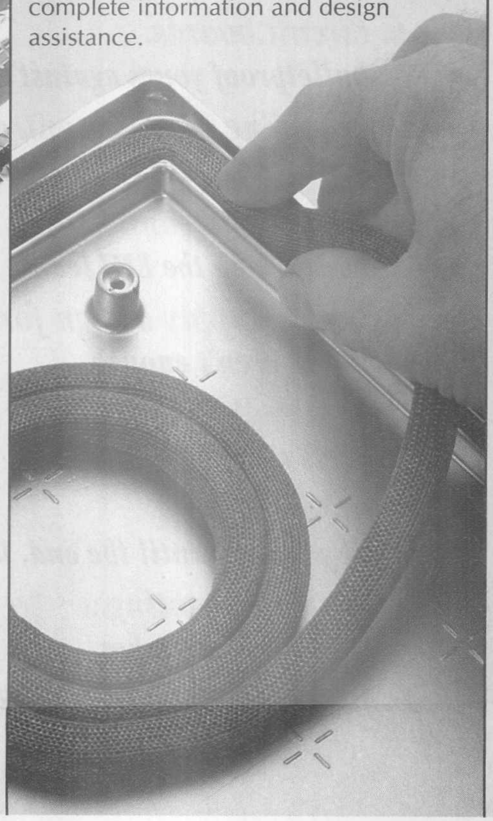
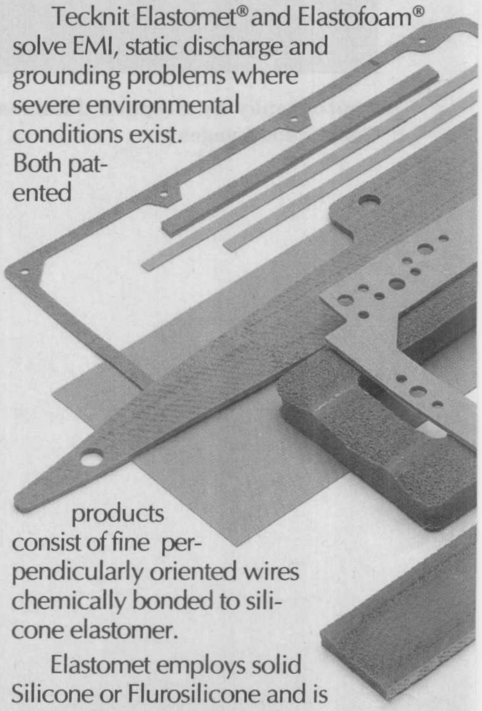
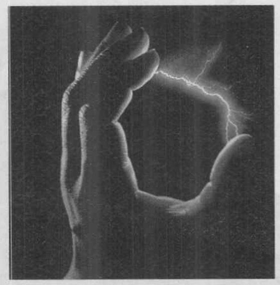
The Designer's Guide to Electromagnetic Compatibility

—Daryl Gerke, PE, and Bill Kimmel, PE,
Kimmel Gerke Associates Ltd, St Paul, MN









Why did we write this series, anyway?

As consulting engineers specializing in electromagnetic interference (EMI) design issues, we encounter a lot of misunderstanding and misconceptions about EMI. Between us, we've been addressing EMI problems for over fifty collective years; for the past six years we've done nothing else. We've solved hundreds of EMI problems and prevented hundreds more. We've written dozens of articles and taught dozens of classes on the subject. Yet we still see many of the same problems over and over again. Many of them could be avoided at little or no cost with simple design techniques.

When EDN issued a call for articles last year, we saw an opportunity to share some of our hard-earned EMI knowledge with our design colleagues in the electronics industry. We believe the time has come in our careers to give something back to our profession. It's been a lot of work—much more than we realized when we began. We're sure anyone who has struggled to write a paper or technical report can appreciate this.

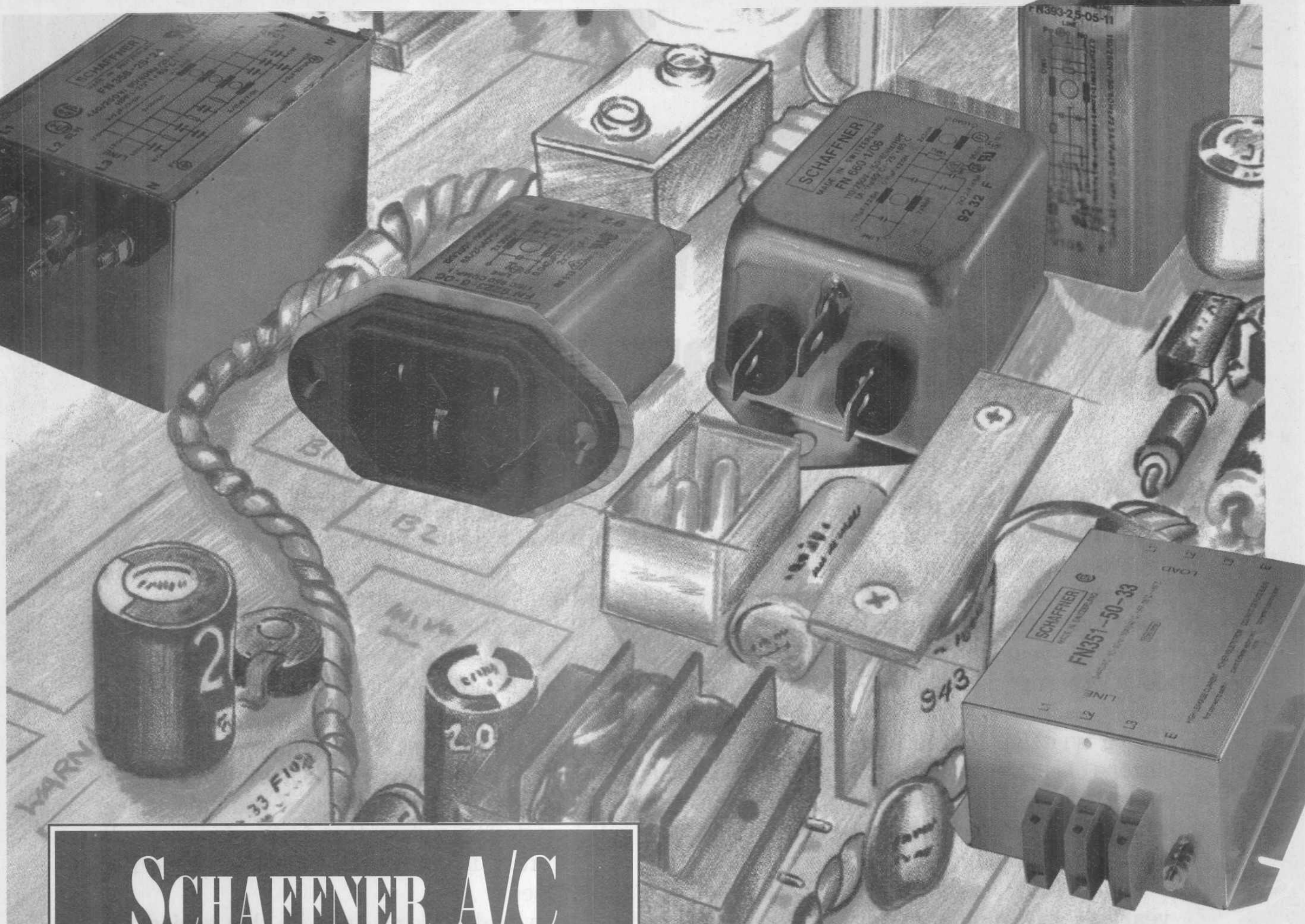
We've taken a nontraditional approach to EMI in this design guide. You'll see very few equations (no integrals or partial differential equations), and you won't find excruciating details on EMI rules and regulations. There are already many fine books on EMI covering those subjects, and we didn't want to duplicate them. Most of you just want help with your designs—you don't want to become an expert in electromagnetic field theory. Our focus is on practical insights and ideas about EMI to help you identify, prevent, and solve your EMI problems as you design your equipment.

We confess that we were inspired by Bob Pease's series on Troubleshooting Analog Circuits that appeared in EDN several years ago. We liked his direct, folksy style. Reading his articles was almost like having a conversation with a friend over coffee. No heavy formulas or exotic theories—just a lot of common sense. We've tried to capture that feeling here as well. If imitation is a form of flattery, we hope Bob is pleased.

In an undertaking such as this series, it's always appropriate to thank those who have contributed to your success. There have been many who have graciously shared their time and knowledge of the EMI field with us. Some of these special folks include Tom Chesworth, Norm Violette, Michael King, Ron Brewer, Bill Parker, Bill Ritenour, Don Sweeney, Don White, Don Keating, and Dan Hoolihan and all the gang at Amador. Thanks to all of you, and thanks to Steve Leibson, Editor-in-Chief at EDN, who has patiently supported this project from the beginning.

Finally, a special word of thanks to our wives, who stood beside us when we started our EMC consulting firm and who have pitched in to make it a success. Mary Lou and Sharon, this series is dedicated to you.

Daryl Gerke, PE, and Bill Kimmel, PE
Kimmel Gerke Associates Ltd
St Paul, Minnesota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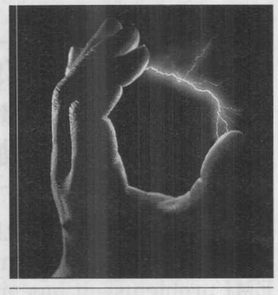


The Designer's Guide to Electromagnetic Compatibility

Chapter 1

Noise and interference: a different game

There are two types of design engineers—those who have had electromagnetic interference (EMI) problems and those who will. Regardless of which category you are in, you probably feel that EMI is a black art that defies logic, science, and perhaps even reason.

But like most technical problems, there is an underlying sense of order. There are rules and strategies and even regulations, thanks to government intervention. It's really just a game, and with some fundamental knowledge and insight, you can learn the EMI game. With enough time and practice, you can become a pretty good player.

That's what this series is all about: how to play the EMI game. It's a game we've played collectively for over fifty years. Since 1987, we've been full-time consulting engineers specializing in solving EMI problems. No, we're not EMI test engineers—*we're design engineers like you, and our focus is on identifying, preventing, and fixing EMI problems at the design and systems levels.* Because of that focus, we've seen some patterns emerge that can help you understand and solve EMI design problems. We've also encountered some myths and misunderstandings that only confuse the issues. We plan to share some of that hard-earned knowledge with you, our colleagues in design.

This series is a tutorial, not an in-depth treatise on EMI. It's aimed at the designer (not the EMI expert), and it's about EMI design issues (not testing or exotic theories.) We plan to cover the EMI game in 12 chapters. The first five deal with the most common EMI problems and their impact on designs; the second five focus on EMI design at the board and box level; and the last two deal with testing and troubleshooting EMI problems.

One caution—we can't make you a 20-year EMI expert in 12 easy lessons, but we hope we can help you better understand the EMI game, and how to play to win.

What is this game called EMI?

If you're going to play any game, you need to know the rules. You also need to know the underlying philosophy of the game.

With some fundamental knowledge and insight, you can learn to play the EMI game.

Let's start with a few simple definitions.

EMI, or electromagnetic interference, is a problem. Simply stated, a piece of electronic equipment doesn't work as it should because of unwanted electrical energy in the wrong place at the wrong time doing the wrong things. EMI is a kind of electronic juvenile delinquent.

EMC, or electromagnetic compatibility, is the solution. Simply stated, a piece of electronic equipment works as it should in its intended electromagnetic environment. At the same time, the equipment doesn't cause problems for its electronic neighbors. EMC is a kind of electronic nirvana.

RFI, or radio frequency interference, is a rather dated term for EMI. It harkens back to an earlier time, when most electronics used vacuum tubes (remember them, they glowed in the dark?), when most interference problems were related to radios. Later, we had TVI, or television interference, and then finally the more general term, EMI. We'll use the term RFI to mean interference to and from radio transmitters and receivers.

The terms, EMI, EMC, and RFI are often interchanged. It's not a big deal, but we'll be precise here. You should be careful with these terms, too. We've had instances where part of the problem was in the communication; our clients said one thing, and we heard another. We need to be sure we're all using the same language.

Several more terms need a quick introduction. *Emissions* refer to energy originating from your equipment, which can be either radiated or conducted. *Susceptibility* refers to external energy affecting your equipment; *immunity* is another common term for susceptibility, which can be either radiated or conducted.

Some EMI philosophy

One or our favorite discourses on philosophy in electronics was written by Bob Pease and appeared right here in *EDN*. In his article *Philosophy of Troubleshooting,* Bob states that "...a significant part of effective troubleshooting

The Designer's Guide to Electromagnetic Compatibility

lies in the way that you think about the problem." So it is with troubleshooting EMI problems—it has much to do with how you think, not what you think. Here are four philosophical points about EMI that we want to emphasize.

Point 1: EMI is complex, but not complicated

Many designers see EMI as an arcane art, or worse. But in reality, all EMI problems can be explained by the basic laws of physics. Furthermore, once the underlying principles are understood, most EMI issues are really quite simple. Throughout this series, we'll use simple models to explain many common EMI problems. Those problems can become complex, however, because there are many variables, often with subtle and unexpected interactions. These variables can add up quickly, resulting in hundreds or thousands of possibilities for even simple situations.

For example, look at something as basic as a shielded cable. That's not too complicated, but even so, EMI questions quickly arise. Should I ground the cable shield at one end, both, or neither? If I do ground the cable shield, where should I place the ground? What about ground loops? Should I use braid- or foil-shielded cable? What about double-braided cable? Can I use plastic connectors, or should I use metal? Can I connect the signal ground to the shield ground? Should the wires in the cable be twisted pairs? Should they have individual shields? Will a ferrite help? We're already up to several thousand possible combinations with these questions alone.

The real challenge then is not in the physics but in narrowing the possibilities to a reasonable number. We'll start looking at that shortly, when we develop a diagnostic framework for EMI problems.

Point 2: EMI is about exceptions to the rules

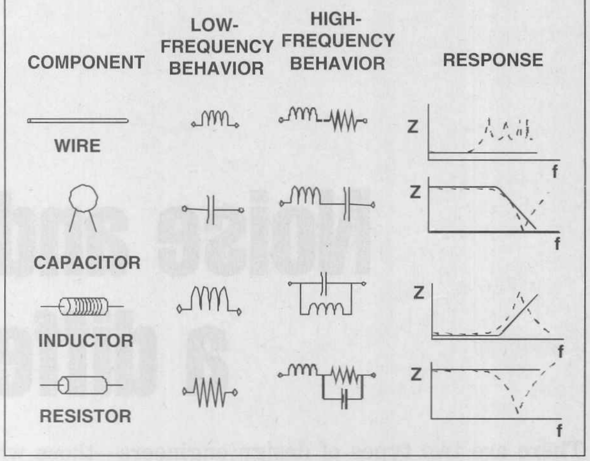
It's very common in the design world to develop design rules. Just follow these rules and you won't have any problems, right? If only real life were so simple.

Design rules work most of the time. Unfortunately, EMI problems often occur even when you follow all of the design rules. You cry "foul" but to no avail. *EMI problems are often the result of exceptions to the normal rules.*

For example, when is a bypass capacitor not a bypass capacitor? When it's an inductor—due to lead length—at high frequencies. When is an inductor not an inductor? When it's a capacitor at high frequencies. When is a ground not a ground? When it's a sneak path for unwanted noise, often at low frequencies. When is a cable not a cable? When it's an antenna, particularly at multiple self-resonant frequencies.

We often refer to these exceptions as the *hidden schematic.* Too often, we assume that the components will be perfect at all frequencies; they are not. Too often, we assume that mechanical packaging will be perfect shields; they are not. Many times, "EMI exceptions" occur when you bend or break the rules. See **Fig 1** for a detailed look at a hidden schematic.

Fig 1—Hidden schematic effects



Modifying design rules can help some of the time, but even then you can miss that one exceptional case with resulting EMI problems. Your safest course with EMI problems is to assume that any of the normal rules might have been broken. There is, however, a silver lining. If you can find the broken rule, it's often very easy to fix the problem.

Point 3: EMI is an easy necessity

Many designers take great pride in the elegance of their creations, and rightfully so. In spite of what the non-technical world may think, we often see real beauty and art in our scientific accomplishments.

And then along come those dirty little EMI problems. They force us to put in extra components, such as filters, that seem to contribute nothing to the design. These problems force us to route cables or wires in complex ways. They force us to add shielding, which adds cost and weight and complicates other design issues such as ventilation. Worst of all, they force us to think about all the dire possibilities and consequences of how our designs might ultimately be used.

Unfortunately, this messiness is often necessary if our creations are to work in the real world. Furthermore, isn't that what engineering is all about: using technology to provide real-world solutions to real-world problems? If those problems include EMI, so be it—we must prevent and solve them. You can't afford to ignore EMI problems, messy or not.

Point 4: EMI needs a different view

The final point to be made is that EMI often calls for a different way of looking at things.

By now it should be apparent that the EMI game is different from the design game. It has a different set of rules and objectives.

We are very fond of analogies. The simpler and cornier, the better. We'll be sprinkling some of our favorites throughout this series. Some are borrowed, and many are our own demented creations, probably the result of too many late nights agonizing over weird EMI problems.

The following analogy is borrowed from a good friend and colleague, Dr Tom Chesworth of Seven Mountains Scientific Inc. Tom uses the games of chess and poker to compare the games of design and EMI. Chess (design) is a

game of strategy played in a sedate environment, while poker (EMI) is a game of tactics and odds played under pressure in a smoke-filled room. Each game has its own rules, and it takes a shift in thinking to switch from one game to another.

Tom stresses that in poker (and EMI), it's possible to lose with a good hand, yet win with a poor hand. Furthermore, the real problem is not in the cards we can see but in those we cannot see. We may need to hedge our bets (such as designing for threats that may or may not be there), and we may need to take some chances (such as experimenting when troubleshooting). Every game is different, but if we win more than we lose, we can play again tomorrow.

So it is with EMI problems. You need to shift your thinking if you want to stay in the game. You'll have a lot more success and a lot less frustration. Who knows, you might even start to enjoy an occasional game of EMI.

Enough philosophy for now. It's time to move from the abstract to the concrete. It's time to identify key EMI problems and how to attack them. In the remainder of this chapter, we'll look at a method of classifying EMI problems, and we'll take a quick look at the most common EMI problems that designers face today.

Developing a diagnostic framework

EMI problems vary widely. You've likely faced several yourself. Last month the production line was down due to power glitches; this month, your new product is failing an FCC test; next month, you'll get a call about flaky field problems with a product that's several years old. All of these problems are different but all of them caused by this thing called "EMI."

So how do you organize the information about these diverse problems? What do they have in common? How do they differ? What additional information do you need? How can you start to make some sense out of all this chaos?

One way is to approach EMI problems the same way a doctor approaches medical problems. You need to diagnose the problem before you can prescribe a solution. (If this is starting to sound like another analogy, it is.) But you can't ask just any old question. You need to organize the information you obtain. You need a **diagnostic framework,** a skeleton on which to hang all that information.

In our consulting work, we use a simple model that is quite popular in the EMI engineering community, the "source-path-receptor" model. Simply stated, you need three elements for an EMI problem:

- There must be a source of energy
- There must be a receptor that is upset by the energy
- There must be a coupling path between the source and receptor for the unwanted energy.

All three must exist at the same time; if any one of the three elements is missing, you don't have an EMI problem. Sometimes you can identify all three elements. Other times you can only guess. This may seem like a simple model, but it does help organize your information.

Figs 2 and **3** illustrate this model, giving typical sources, paths, and

High-order effects and EMI

We've already seen that inductors and capacitors can behave in unexpected fashions at high frequencies. But even "noncomponents," such as wires, connectors, or even circuit traces, get into the EMI act, resulting is some very interesting EMI phenomena.

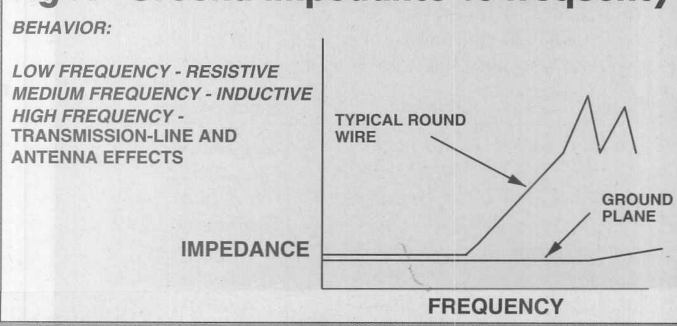
Look at the behavior of a simple 1-ft piece of wire or board trace over a broad frequency range, say dc to 1 GHz (**Fig A**).

At low frequencies, a 1-ft piece of wire is a low-impedance (almost 0Ω) resistor. It's so insignificant that we often don't even bother including it in a schematic. At frequencies above about 10 kHz, however, the inductive impedance per inch of that same wire now exceeds the resistive impedance per inch. As the frequency increases, so does the inductance. Now we have a second-order effect to contend with as our insignificant 0Ω resistor becomes an inductor with a significant impedance.

As we increase frequency (or use digital signals with increasingly faster rise times), that same piece of wire starts to behave like a transmission line. We must now account for the third-order effects of reflections and characteristic impedance. That same piece of wire may also radiate as an antenna, or it may couple energy to nearby wires through crosstalk. Things get really dicey at microwave frequencies where a zigzag in a wire trace can actually result in an antenna with gain. Both transmission-line effects and antenna effects are functions of length, relative to rise times or wavelengths.

It's not possible, of course, to account for all of these effects all of the time. If we did, we'd never finish a design, because we'd be forever analyzing the system. We do need to be aware of these higher-order effects, however, and their potential to cause significant EMI problems.

Fig A—Ground impedance vs frequency



receptors you'll likely encounter. As you can see, there are many possibilities, but keep in mind that not all combinations cause problems.

The second part of the diagnostic phase is to flesh out the information. There are a number of parameters that can affect your diagnosis. For example, how sensitive is your circuitry? What is the frequency content of the threat? How long are the cables?

We try to gather information on at least five key parameters, which we dub "FAT-ID," an abbreviation that stands for frequency, amplitude, time, impedance, and dimensions. Later in the series, you'll read more about "fatness" and EMI, so this makes a good EMI mnemonic (or maybe a bad pun).

Frequency—This is a key parameter for any EMI problem. If you have an EMI problem with a communications system (or an FCC/VDE failure), you may know the exact frequency. At other times, you may need to guess or make an estimate. As a quick rule of thumb, the higher the frequency, the more likely the coupling path is radiated; the lower the frequency, the more likely the coupling path is conducted.

Amplitude—This is also a key parameter for any EMI problem. You need to assess both the source and the receptor together on this one. The worst combination is a strong source (such as a nearby high-powered radio transmitter) near a very sensitive receptor (such as microvolt-level instrumentation). On the other hand, a weak source near a insensitive receptor may not cause an EMI problem.

Time—This parameter has two dimensions, long term and short term. For the long term, we need to determine whether or not there is a cause-and-effect relationship. Do the lights dim only when a motor is turned on? (Suspect a power disturbance.) Do upsets occur only when someone touches the unit? (Suspect ESD.)

For the short term, we need to look at rise times and clock rates. These can be converted to equivalent "frequencies." Generally, we like to work in the frequency domain rather than the time domain for EMI problems. We'll look at this in more detail later, but if you can't wait, a good rule of thumb is to use an equivalent EMI frequency of $1/(\pi \times \text{rise time})$ for digital signals and transients. For 1-nsec logic, the equivalent EMI frequency is more than 300 MHz. No wonder we have EMI problems with high-speed systems.

Impedance—Another key parameter you should determine is circuit impedance levels of both the source and receptors. Similar source-receptor impedance levels are more likely to result in problems than a source and receptor with different impedances because high-impedance sources have minimal impact on low-impedance receptors and vice versa. Similar rules apply to radiated, or field, coupling. High impedances are associated with electric fields; low impedances are associated with magnetic fields.

Dimensions—The last key parameters to gather are the physical dimensions, particularly cable lengths (which act as antennas) and enclosure openings and seams (which act as "slot" antennas). Take a critical look at parallel cable or wiring runs (possible crosstalk), and even short wires on ground paths or cable pigtails. What you're looking for here are lengths that represent significant fractions of a wavelength (the higher the frequency, the shorter the wavelength) or significant fractions of a "rise-time distance" (the shorter the rise time, the shorter the distance). In the latter case, it helps to realize that 1 nsec translates to about 1 foot in free space and about 6 inches on a board.

So there you have it—a quick and dirty way to organize our data on an EMI problem. Source, path, receptor, and the FAT-ID parameters. Keep in mind, you may not have all the answers right away, but it helps to know which questions to ask in the first place. Remember, at this point you're like a doctor trying to make a preliminary diagnosis. (This step is important—you would not want a doctor to prescribe a drug without even listening to your symptoms.)

Our advice is to gather as much information as you can and then sort through it. You may need to go back and gather more information or you may even need to take a guess. The more information you gather, the better your chances for a good diagnosis in the first place.

Fig 2—Source-path-receptor model

Any interference problem can be broken down into

- the SOURCE of interference
- the RECEPTOR of interference
- the PATH coupling the source to the receptor

Sources	Paths	Receptors
Microcontroller • analog • digital ESD Communications Transmitters *Power disturbances* Lightning	Radiated • EM fields • crosstalk capacitive inductive Conducted • signal • power • ground	Microcontroller • analog • digital Communications • receivers Other electronic systems

Fig 3—Three types of interference

Emissions-immunity-internal

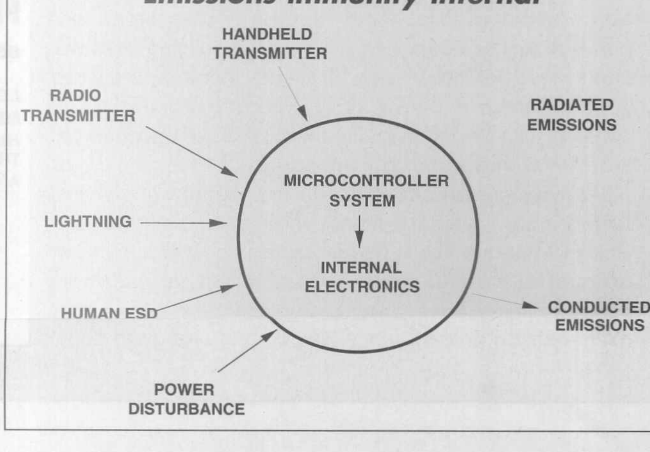


Fig 4—Five key threats
(with typical levels)

(1) Emissions/Government regulations	
FCC Part 15	Radiated=30-300 mV/m
VDE 0871	Conducted=250 mV-3 mV
(2) Electrostatic discharge (ESD)	
IEC 801-2	10-15 kV
(3) RF fields	
IEC 801-3	1-10V/m
(4) Power disturbances	
IEC 801-4	4 kV EFT
IEEE C62.41	6 kV lightning surge
(5) Self compatibility	
Analog	mV-mV
Digital	0.4-1V

Five key threats facing designers

As the final part of this introductory chapter, we'll identify five key problem areas (**Fig 4**). There may be a few more problems lurking about, but these five should cover 95% of the EMI problems you'll encounter. We'll give each of these a quick overview here and then later explore each in more depth.

Threat 1—Regulations

Anyone who has ever failed an FCC or VDE test appreciates this threat. While it may be a pain to meet these requirements, it's chilling to think what our "electromagnetic environment" might look like today without these requirements. Regulations can include both emissions and immunity, as shown in **Fig 5**.

When most designers think of EMI regulations, they think of the FCC/VDE emission regulations. In the most general form, these regulations are designed to protect the radio spectrum and limit "spurious" radiation from both *intended radiators* (such as transmitters) and *unintended radiators* (any electronic system.) In the good old days (pre-computer), most unintended radiators were not much of a problem. The proliferation of computer clocks (oscillators) and cables (antennas) has changed the game drastically over the past few years. The microprocessor explosion in the mid-1970s led to a corresponding explosion in complaints of EMI problems with licensed communications systems. Most of these problems were television related, although there are a number of horror stories involving inadvertent computer jamming of aircraft or police communications.

These problems soon resulted in very specific regulations that limit the emissions from computer or microprocessor-based equipment. In the United States, these are the infamous FCC Part 15 regulations. In Japan, these are the VCCI (Voluntary Control Council for Interference) limits that are no longer voluntary. In Europe, the VDE (Verband Deutscher Electrotechniker) or West German regulations have been a driving force, although they will soon be replaced by the EC (European Community) regulations. Incidentally, the Germans have led the rest of the world in attacking this problem; the VDE has had mandatory emissions regulations for over 40 years.

Remember, most of the commercial EMI regulations today are based on controlling *emissions* and are only aimed at protecting a nearby television or broadcast radio receiver. Once again, the Europeans are leading the charge, and are mandating immunity tests as part of the EC regulations. The military has had mandatory EMI regulations for years (both emissions and immunity), and most military designers are well versed in meeting these requirements. The automotive industry has adopted strict voluntary requirements (emissions and immunity) based on real-world constraints faced by their equipment. The medical industry is coming under increasing scrutiny from both the FDA in the United States and overseas from the EC through a special medical-device standard.

The bottom line is that EMI regulations are here to stay and they will likely get tougher in the years ahead. The good news is that meeting these requirements usually results in a more robust and more reliable product.

Threat 2—RFI

In this series, we'll use the term RFI, or radio frequency interference, to describe the problem of interference to a system from a nearby transmitter. In terms of our diagnostic model, the source is a radio transmitter; the path is electromagnetic radiation traveling through air (or space); and the receptor is a system that is upset by the RF energy.

RFI is a serious threat to all modern electronic systems, due in large part to the proliferation of radio transmitters. These transmitters include both large, high-power systems (television, radar, telemetry) as well as small, low-power systems (handheld radios and cellular telephones). This threat is particularly acute with sensitive monitoring systems, which can be overwhelmed by a nearby source of RF energy.

The problems are not always with high power and big antennas. In fact, most of the problems we see today are caused by low-power handheld radios that are operated close to the equipment. The key parameter here is field strength, which is a function of both the transmitter power and the distance from the antenna. Typical equipment failure levels are at electric field strengths of 1 to 10V/m. As a rule of thumb, a 1W radio at 1m has a field strength of about 5V/m, so problems with small handheld radios can and do occur.

The European immunity limits are in

Fig 5—EMI regulations

Commercial regulations
- mandatory
- past focus—control emissions
- future focus—emissions and immunity

Military regulations
- contractual
- control both emissions and immunity

Automotive regulations
- voluntary
- control both emissions and immunity

Medical regulations
- voluntary, but becoming mandatory
- control both emissions and immunity

the 1-10V/m range, so they are quite realistic. Meeting these levels can be difficult, however, and they require careful attention to EMI design details. Simple FCC/VDE approaches are woefully inadequate.

Threat 3—electrostatic discharge

ESD is also a serious but very realistic threat to modern electronic systems. Incidentally, in this series, we'll use the term ESD to describe the actual discharge to a system, not to individual components.

It no longer takes a *direct discharge* to cause problems; the intense electromagnetic field from a nearby indirect discharge can easily upset a system. We've seen this effect from discharges up to 20 ft away. Typically, the indirect discharge causes upsets, while the direct discharge causes upset or damage. The damage may be immediate or latent, waiting to get you later.

An ESD event is very rapid, typically with 1- to 3-nsec rise times and peak currents in the tens of amperes. It's both the high currents and high rates of change that cause EMI problems. ESD is considered a high-frequency problem: at 1 nsec, the "equivalent EMI frequency" is over 300 MHz. The rule of thumb may not give a fast enough equivalent frequency for all cases, though. Recent ESD tests have measured some ESD spikes in the 100-psec range. This would push the "equivalent EMI frequency" well into the gigahertz range.

Electrostatic discharge should be considered in any new design regardless of whether it is required by regulations. The laws of physics dictate that ESD will be an EMI problem.

Threat 4—power disturbances

Power disturbances are emerging as a serious EMI problem for all electronic systems. It's not that the environment is getting worse, but rather that modern electronic systems are becoming more vulnerable to power-line disturbances. The problem is compounded by the lack of definitions and guidelines, al-though this is be-ginning to change.

Power guidelines range from simple "high/low" voltage limits to more sophisticated requirements, such as the EFT (electrically fast transient) or the lightning surge transient. EFT simulates arcing and other "high-speed" noise that can play havoc with microprocessor-based systems. The high speed is usually ignored by older, slower electronics. The lightning transient test can be destructive, but then so can an actual lightning hit to the system power lines.

Analog and digital circuits respond differently to power disturbances. This difference can cause some confusion. Digital circuits are easily fooled by spikes, while analog circuits can be fooled by sags and surges. Both can be affected by severe long-term sags, which starve the power supply of needed energy.

There is a new concern over power-line harmonics, caused by nonlinear loads such as switched-mode power supplies or other "electronic" loads. These loads typically consume power at the peak of the cycle, rather than over the entire sine wave. The varying load can generate harmonics and waveform distortions that stress the power distribution system. As a result, new regulations and guidelines are emerging for power-line harmonics.

Threat 5—self compatibility

The final key threat is incompatibility internal to the system. This includes problems with mixed technologies, such as analog/digital, or motors/relay/digital. In the first case, the digital circuits typically jam the analog circuits. In the second case, the motors and relays jam the digital circuits. There is a third case, high-speed digital, where the digital circuits jam themselves.

Although most designers are well aware of these problems, they may not be considered EMI problems. Nevertheless, many of the same EMI-preventing design techniques can be applied equally well to problems entirely inside the system. Remember, the laws of physics don't care where you draw the boundaries.

Finally, many EMI problems can be prevented by attention at the internal levels. Prevention can save you money, too. A few cents spent for decoupling capacitors in critical circuits is much cheaper than several dollars in shielding or filtering, and probably results in a more solid design as well.

Remember, every EMI problem ultimately begins or ends at the circuit level. EDN

Key points

Develop an EMI philosophy
- ☑ EMI is complex, but not complicated
- ☑ EMI is about exceptions to the rules
- ☑ EMI is a messy necessity
- ☑ EMI requires a different view

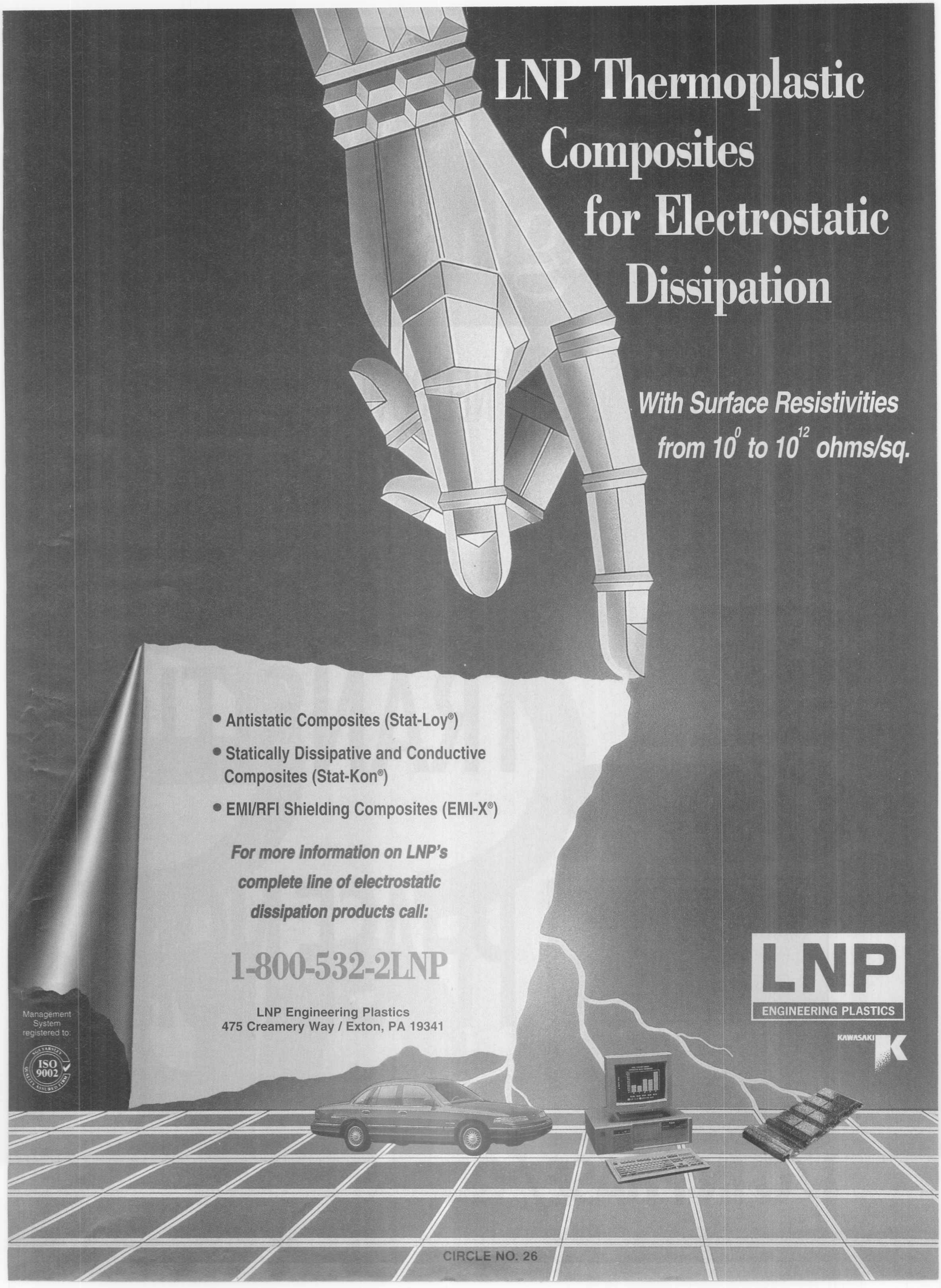
Three elements of an EMI problem
- ☑ Source/path/receptor
- ☑ Key parameters—FATID

Five key EMI threats facing designers today
- ☑ Regulations
- ☑ Radio frequency interference
- ☑ Electrostatic discharge
- ☑ Power disturbances
- ☑ Self-jamming

Every EMI problem begins and ends at a circuit.

That's it for our first session. We've shared some bits of philosophy as it applies to EMI problems and given you a diagnostic framework to assess problems. We've also given you our view on five of today's key EMI problem areas. We hope this helps you understand why EMI is important and how to begin to attack the problems.

In the next several chapters, we'll look at each of the key threats in more detail. We'll focus on how to identify the problems and how to prevent or fix the problems. Later, we'll provide details on designing boards, cables, enclosures, and power supplies for EMI. We'll conclude the series with some thoughts on testing and troubleshooting EMI problems.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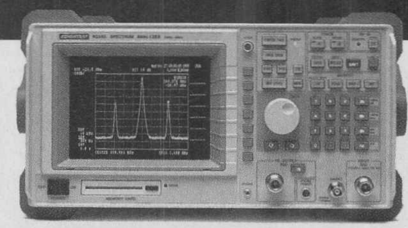

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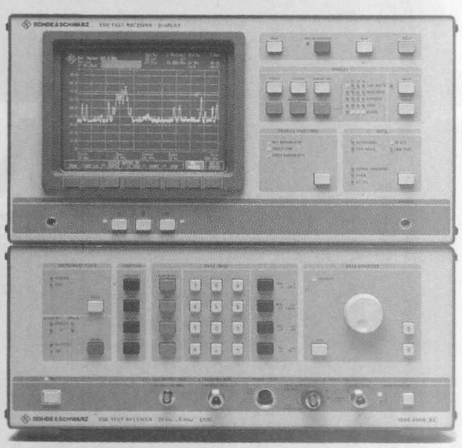

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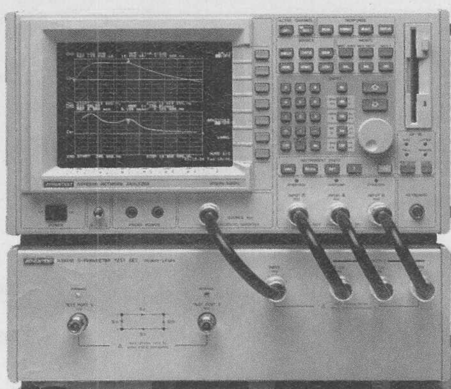

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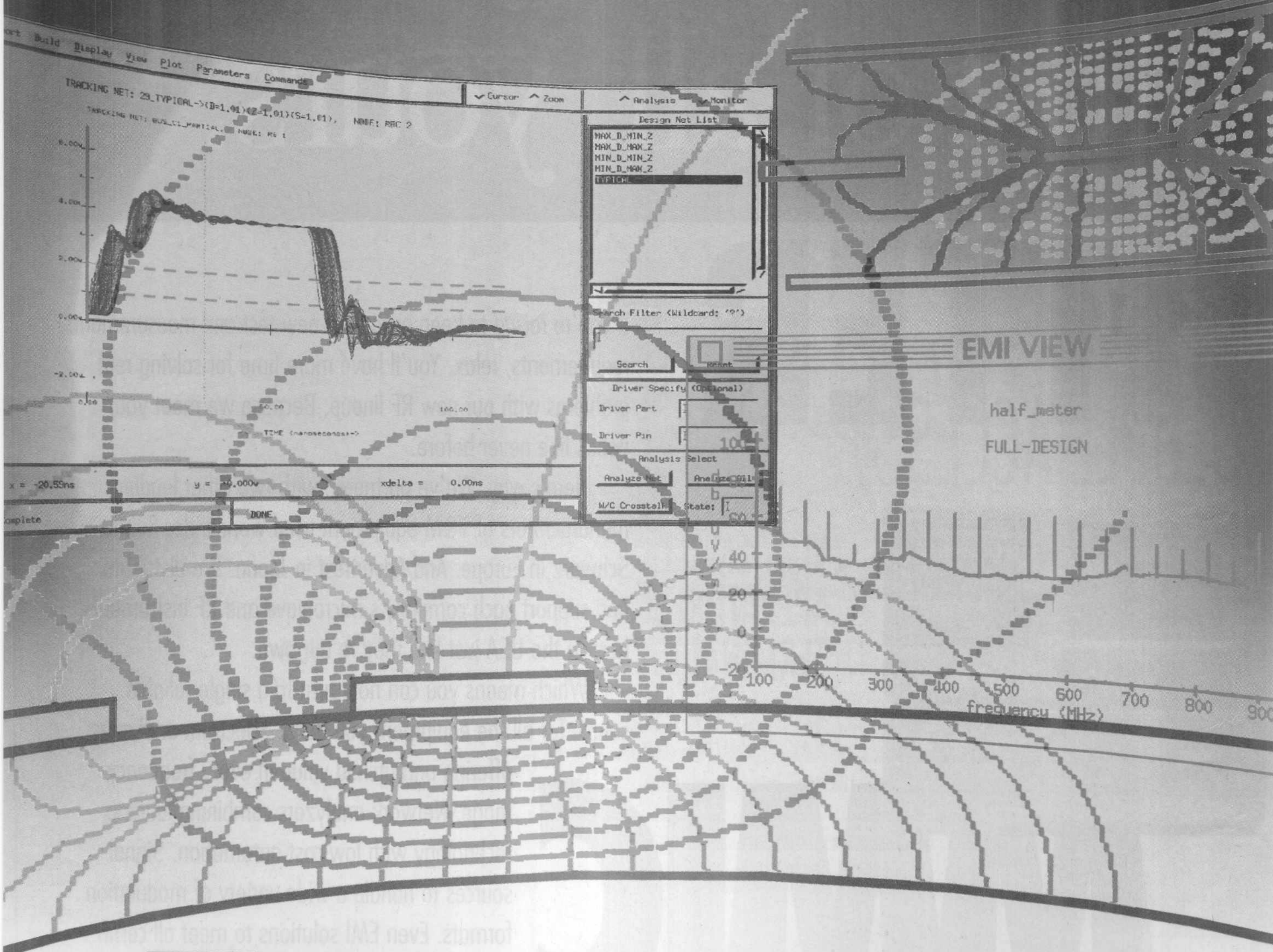

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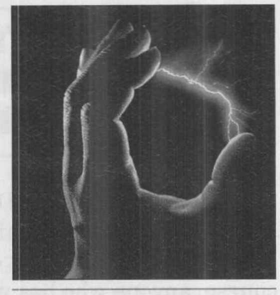


The Designer's Guide to
Electromagnetic Compatibility

Chapter 2

EMI regulations...why, where, and what do they mean

Most of us have a love-hate relationship with rules and regulations. We love them when they provide a simple answer to a problem, but we hate them when they force us to do something we'd rather not do. Besides, rules and regulations are OK for the other guy, but I want complete freedom for my designs, right?

Well, regardless of how we feel about them, EMI rules and regulations are here to stay. The rules exist because there are real EMI problems in the real world that must be addressed. Noisy systems interfere with communications systems, some of them critical, such as public safety or aircraft navigation and communications. At the same time, today's electronic systems are often vulnerable to external effects such as electrostatic discharge, power disturbances, or licensed radio transmitters. We need guidelines to assure that we can all work together in an increasingly complex electronic society. Actually, the rules and regulations often result in products that are designed better.

The problem we see with most EMI rules and regulations is that they are legalistic. They very carefully set precise limits and test procedures, but they don't give any design guidance. They tell you *what limits you must meet,* but not *how to meet them.* Nor do they explain why the rules are important. This situation is a little like taking a trip without a map or even a reason for going in the first place. The regulations may meet the needs of the test engineer but they often leave the design engineer high and dry (see the **box**, "EMI design engineering vs EMI test engineering", pg S18).

In this chapter, we'll focus on the *why* and the *how* of EMI regulations, not the specific limits. There are already many good articles that address EMI test procedures and limits. Instead, we'll look at EMI regulations by industry and marketplace and we'll share our perspectives on what these various rules and regulations mean to you as a designer. We'll be taking a systems approach, and we'll examine the impact on design issues. As a caveat, we won't be able to answer your detailed design questions in this chapter, but we will address those issues in later chapters. Our goal in this chapter is give you a broad perspective on what EMI regulations mean to you and your designs.

Actually, the rules and regulations often result in products that are designed better.

Why do we need EMI regulations, anyway?

In simple terms, we need EMI regulations because of *electromagnetic pollution.* Electronic systems are proliferating and system speeds are increasing while electronic devices are shrinking. There are more and more sources of electromagnetic noise. These sources generate noise at higher levels and have lower levels of resistance to that noise. The EMI problems are not going to go away, and if we do nothing, they will only get worse.

Fortunately, EMI pollution immediately abates when you get rid of the source or the receptor. The Environmental Protection Agency has no need for an EMI Pollution Superfund, at least for now. Unfortunately, we usually cannot just kill the source or receptor; it's probably there for a good reason. The world isn't going to stop using radio transmitters just because your design gets upset by a little RFI. And the world isn't going to stop watching television just because your design can't keep its own RF signals to itself. Nor are the rules of physics going to be suspended to accommodate your lack of design concern over ESD, power spikes, or electromagnetic radiation.

You don't want to overdesign, either. As engineers, we're dealing with the real world and we need some real-world guidelines on the electromagnetic environment. That is where EMI rules and regulations can actually help us. Most EMI regulations are based on preventing specific problems in a given environment. Believe it or not, much thought and debate goes into establishing all those EMI regulations. Knowing that, we can actually take advantage of all that work to establish practical EMI environmental goals for our products.

EMI rules and regulations can be either *mandatory* or *voluntary.* Probably the most familiar mandatory limits are the FCC (Federal Communications Com-

mission) and the VDE (Verband Deutscher Elektrotechniker) emission limits that apply to most computers. Of course, anyone who has worked on military designs is well aware of MIL-STD-461, a mandatory but negotiated set of limits. Voluntary limits exist for the medical, automotive, and industrial-control industries, although some of these limits are now becoming mandatory as EMI problems increase. With mandatory limits, you have no choice but we strongly encourage you to adopt the applicable voluntary standards, too.

One final point before we look at EMI regulations in detail: cultural differences affect EMI regulations. Specifically, because Europe tends to regulate more than the United States or Japan, the European EMI regulations are generally stricter and have fewer exceptions than the US or Japanese EMI regulations. For example, the European Community (EC) is making immunity to RF, ESD, and power disturbances mandatory; the US and Japan do not address these EMI issues. And it's generally agreed that Germany's VDE is more restrictive than the United States' FCC. In today's global marketplace, it's important to understand and respect these different cultural views.

For the remainder of this chapter, we'll look at the EMI requirements of five different market areas. While the technology for each of these markets may be similar, the EMI environments, attitudes, and design approaches vary widely.

EMI and commercial products

The commercial market includes electronic equipment used in the home and business environment. This market includes personal and commercial computer systems, business equipment, home entertainment systems, home appliances, and many other gadgets. The environment is relatively benign and the products are usually cost-sensitive, high-volume types. The cost of failure is typically low, and a small number of nuisance failures might well be tolerated.

Most commercial EMI regulations focus on emissions. Interference to home radio and television receivers is a key problem in the commercial market. In fact, when the home computer market exploded in the late 1970s, so did the complaints of television interference. Because the FCC is responsible for protecting the radio spectrum, it needed to respond quickly. The response was the well-known Part 15 rules that limit both conducted and radiated emissions from computers.

The distinction between conducted and radiated emissions is an important one. At high frequencies (above 30 MHz), only the electromagnetic radiation is measured, while at low frequencies (below 30 MHz), only the power-line conducted noise is measured. This division recognizes the fact that the coupling mechanism between source and receiver will most likely be electromagnetic radiation at higher frequencies and direct conduction at lower frequencies.

The prime objective of commercial regulations is protecting nearby radio and television receivers. This is the main thrust of the FCC, VDE, and VCCI regulations that so many of us must meet. These regulations do not address susceptibility (the common US term) or immunity (the common European term), although this is changing with the new EC directives. Furthermore, commercial emission regulations are often woefully inadequate for protecting nearby communications receivers. We've run into this problem on several occasions, where standard off-the-shelf FCC/VDE equipment was simply too noisy to use near a VHF radio receiver and had to be extensively modified.

An emerging objective is assuring these emitters will not also be susceptible to interference. The EC is now addressing this concern and has issued directives that include immunity tests for electrostatic discharge, radio frequency interference, and certain power disturbances. These requirements will become mandatory after 1995, so if you want to sell your products in Europe, you need to design for immunity as well as emissions. It's doubtful that the US, Japan, or the rest of the world will mandate immunity in the near future for commercial products.

EMI and commercial equipment

- EMI environment: benign
- Economic issues: high volume, cost sensitive
- Cost of failure: typically low
- Key concerns: interference to television and radios
- Regulatory focus: emissions, with immunity secondary
- Design impact: moderate
- Comments: regulations are mandatory. European Community will have major impact by 1996.

EMI and medical equipment

- EMI environment: benign to harsh
- Economic issues: moderate to low volume, cost not critical
- Cost of failure: moderate to severe
- Key concerns: reliable and safe operation of devices
- Regulatory focus: immunity primary, emissions secondary
- Design impact: severe
- Comments: Both FDA and Europe are pushing mandatory regulations. Current leakage has severe impact on design.

EMI and industrial products

- EMI environment: harsh
- Economic issues: moderate volume, not very cost sensitive
- Cost of failure: moderate to high
- Key concerns: reliable and safe operation
- Regulatory focus: immunity, with emissions secondary
- Design impact: moderate to severe
- Comments: regulations are voluntary in United States but mandatory in Europe.

Most commercial EMI regulations are mandatory, not voluntary. The limits are not negotiable, and you either pass or fail—there is no such thing as partial compliance. However, the commercial emission limits are divided into two broad classes: A and B. Class A limits apply to products used solely in business environments, while stricter Class B limits apply to products used in residential environments. If your product can be used in the home, you must use the stricter Class B limits; otherwise, you can use either set of limits. The German VDE gives you a big bonus for meeting the Class B limits: the paperwork is much simpler. If you plan to market in Germany, we recommend meeting the VDE Class B levels regardless of use.

Radiated emission limits for commercial and personal computers

Frequency (MHz)[1]	Class A (30m)	Class B (3m)
30-88	30 µV/m	100 µV/m
88-216	50 µV/m	150 µV/m
216-1000	70 µV/m	200 µV/m

1: For equivalent Class A values at 3m, multiply by 10.

So what's the impact on design?

For most systems, the commercial emission regulations are relatively easy to meet. While anyone who has failed an FCC or VDE test might take issue with this statement, these regulations are really not that tough. OK, the first time can be tough, but once you've been learned from your mistakes, it's pretty straightforward. You need to pay attention to your board layout with particular attention to clocks and other highly repetitive signals. Multilayer boards become important for systems with clock rates faster than about 10 MHz. The system may need a moderate amount of shielding, coupled with some simple filtering on power and signal lines. You may also need shielded cables depending on how well you've executed other parts of your design and on the data rates on the cable itself.

Commercial immunity requirements, on the other hand, are tougher to meet. You need to identify and protect vulnerable circuits such as resets, interrupts, and low-level analog stages. You need to pay more attention to signal and power interfaces, which may need additional filtering and transient protection. Cabinet shielding becomes much more important, particularly for ESD and RFI. Shielded cables and high-quality metal connectors may also become necessary.

The most serious impact on your project may be in not passing the required tests. In our experience, retesting usually means another $25,000 to $50,000 in engineering costs (lab time, your time, rework, travel) plus another 4- to 6-week slip in schedule. Of course, there's also lost market share if you are in a competitive situation, which is common in commercial designs.

EMI and military products

The military marketplace includes electronic equipment used in many different situations, from submarines to outer space and from the desert to the Arctic. Equipment includes computers, control systems, and of course a wide range of radio communications gear. The environment varies from harsh to benign, and the products are usually low volume and not very cost sensitive. The cost of failure may be high, particularly for mission-critical systems.

Military EMI regulations focus on both emissions and susceptibility. Unlike commercial designs, most military applications couldn't care less if they interfere with a nearby television receiver. The military is very concerned, however, with mission success. This means the equipment had better not interfere with vital radio communications and that same equipment must operate under some very trying conditions. MIL-STD-461, the key military EMI specification, emphasizes this dual focus. All test methods are preceded by the letters CS, CE, RS, or RE, which respectively stand for conducted susceptibility, conducted emissions, radiated

EMI and automotive electronics

- EMI environment: extremely harsh
- Economic issues: high volume, extremely cost sensitive
- Cost of failure: moderate to severe
- Key concerns: reliable and safe operation. Secondary issue is interference to onboard AM/FM radios.
- Regulatory focus: immunity and emissions
- Design impact: extremely severe
- Comments: regulations are voluntary but have effect of de-facto mandatory requirements.

EMI and military equipment

- EMI environment: moderate to harsh
- Economic Issues: low volume, not cost sensitive
- Cost of failure: moderate to high
- Key concerns: interference to communications, reliable operation, mission success
- Regulatory focus: both emissions and immunity
- Design impact: severe
- Comments: regulations are contractual and can be negotiated. Need to address at proposal stage.

Key points

- √ EMI requirements differ widely by marketplace.
- √ EMI requirements are based on real-world problems.
- √ Commercial requirements are relatively easy to meet.
- √ Military and industrial requirements are tougher to meet.
- √ Medical requirements are tough and have tough current leakage limits that affect EMI design.
- √ Automotive requirements are the toughest to meet.
- √ Always assess your cost of failure and never compromise on safety.

EMI design engineering vs EMI test engineering

Most design engineers are not EMI experts so they often turn to others for help. But even among EMI experts, there are subtle but important differences. There are two distinct camps: test and design. Both are necessary and, in fact, both complement each other. However, there are differences in attitudes, emphasis, and capabilities.

In the test camp, the focus is on how to test products against EMI regulations. EMI testing requires very precise and repeatable measurements of radio frequency energy. EMI test engineers and technicians are usually well experienced and skilled in test methodology, limits, and procedures. Most can also advise you on common solutions, should your product fail an EMI test. They may not, however, be able to give you detailed design help. It depends on the individual and his or her background and design experience.

In the design camp, the focus is on how to identify, prevent, and solve EMI problems during product design. EMI design requires a unique knowledge of components, circuits, mechanical packaging, and systems engineering. EMI design engineers are usually well experienced in analog, digital, power, and radio frequency design issues, so they are well qualified to help you with design problems. Most EMI design engineers can also advise you on troubleshooting solutions, should you have EMI problems in the field.

Many large companies have in-house EMI specialists (both design and test), while smaller companies may rely on outside EMI experts. In either case, titles can give a clue. Most EMI test laboratories are test focused and most EMI consultants are design focused. While there are certainly overlaps in experience, it's important to understand the test/design dichotomy when seeking help, inside or outside your company. In fact, you may need help from both camps.

susceptibility, and radiated emissions.

Most military EMI regulations are applications specific and can be negotiated. A crucial EMI challenge with military designs is the vast range of applications, environments, and constraints. A space craft is vastly different from an aircraft carrier or a tank. Weight is a concern for airborne applications, while heavy, bulky magnetic field shielding is critical for a submarine. Some of these constraints are clearly in conflict with each other. In order to address these differences, MIL-STD-461 specifies different tests and levels, based on application, environment, and even branch of service.

Furthermore, you can often negotiate these tests and levels. If you can show that a certain test is not relevant or that different test levels should be used, you can request changes. Unlike the commercial world, military EMI requirements are not legal requirements; they are contractual requirements between you and your customer.

So what's the impact on design? Generally, military EMI requirements are tougher than commercial limits. As we discussed earlier, the specific requirements will depend on the environment and application.

Military radiated emission (RE) limits are typically between 10 and 100 times more stringent than commercial limits, while the military radiated susceptibility (RS) limits can be up to 200 times more stringent than commercial limits. As a result, you must give careful attention to circuit-board design, shielding, cables, and connectors. Multilayer pc boards, solid metal enclosures with gaskets, metal filtered connectors, and well-shielded cables are typically required.

The military conducted emission (CE) limits are also more stringent than commercial limits but the conducted susceptibility (CS) limits are even more severe. Wide operating frequency ranges mean large filters that are optimized over a broad spectrum. Special transient effects such as EMP (electromagnetic pulse, a nuclear-weapons effect) can have severe design repercussions on power and signal interface circuits.

The most serious impact for military systems occurs before design even begins; you need to address the EMI design issues at the proposal stage. By the way, as a designer you don't need to know how to do all the tests—that's a test engineer's responsibility. You do need to know which requirements will apply to your design. You should know what you're getting into and if a test even makes sense. Don't assume that your customers know what tests are needed either, especially if you are a subcontractor; they may be looking to you for technical direction. If you don't know what is needed, get some help from someone who does. Later in the project is way too late.

EMI and the medical market

The medical market includes electronic equipment used in home, hospital, and laboratory environments. Equipment ranges from patient-connected monitors or pacemakers to large diagnostic systems such as CAT or MRI systems. The environment ranges from benign to severe and the products are generally not very cost sensitive in the consumer sense. (There may be strong competitive cost pressures, however.) The cost of failure ranges from low to high.

Medical EMI regulations are undergoing significant changes, and we expect to see mandatory EMI regulations in the near future. We expect the primary regulatory emphasis to be on immunity to electrostatic discharge, RF fields, and power disturbances. These changes are being driven by the Food and Drug Administration (FDA) in the United States and the EC in Europe.

The regulatory status for electronic medical products today is simple. In the US, there are no mandatory EMI requirements for medical devices although the FDA has been intervening with selected products. Medical devices are exempt from FCC emission regulations and they are covered only by voluntary susceptibility requirements. In Europe, the VDE does requires medical devices be tested for emissions but not immunity.

The status quo is quickly changing. In the US, the FDA is expected to mandate immunity against ESD, RFI, and

power disturbances in the near future. Draft requirements already exist for patient monitors, which will likely be applied to other medical devices as well. In Europe, the EC is working on a separate document to cover medical devices (IEC 601), which will mandate both emissions and immunity regulations for a wide range of medical devices.

The prime objective for medical products is safe operation. This requirement can mean different things, depending on both the application and the environment. Pacemakers are held to a higher standard than a laboratory analyzer. In the first case, an upset could be life threatening. In the second case, a glitch may simply mean running a test again. Many medical manufacturers already have internal EMI standards for both emissions and immunity. These internal standards are usually conservative and are often more stringent than existing commercial standards. For example, pacemakers are tested to RFI levels that exceed typical military requirements.

Medical products may have current leakage limits, too. Patient-connected devices have very severe restrictions on current leakage. These limits prevent accidental microshocks. Many devices have separately isolated electronic sections, which can create some interesting EMI challenges. For example, where do you ground shields or filters for separately isolated circuits?

So what's the impact on design?

For most medical products, the immunity requirements have much more impact than emission requirements. For patient-connected devices, leakage-current limits can play havoc with filters and shielding.

For immunity, you need to identify and protect critical digital circuits (such as resets or interrupts) and sensitive analog circuits (such as EKG amplifiers). Digital circuits are typically more vulnerable to ESD and power spikes, while low-level analog circuits are very vulnerable to RF electromagnetic fields. Power regulators and higher-level analog stages can also be affected by strong RF fields so they may need attention, too.

You'll also need to pay attention to shielding, filtering, and signal cables and interfaces. For patient-connected devices, you'll need special power filters approved for medical applications.

We've found that special design techniques may also be necessary. These include internal shielding, isolation, or internal ESD protection. It can be tricky to meet both EMI and current

Derivation of commercial radiated EMI limits

Believe it or not, most EMI regulations have solid engineering behind them. Most are designed to solve real-world problems by providing adequate design margins. While these regulations can't eliminate every EMI problem, they can greatly decrease the probability of a problem in the field.

A good example of this engineered approach can be seen in the radiated emission limits for commercial and personal computers. Anyone who has failed an FCC or VDE radiated-emission test has probably questioned these limits, but they do make a lot of sense. These primary goal of these commercial limits is to prevent interference to nearby television and radio receivers. By making several assumptions, a very reasonable set of limits can be obtained. The model for these assumptions is shown in **Fig A.**

The first assumption is that interference above 30 MHz will be through electromagnetic radiation, and that low frequency interference below 30 MHz will be through power-line conduction. This assumption is quite reasonable because cables act as efficient antennas at higher frequencies at higher the frequencies. It's also a reasonable assumption because most TV reception is above 30 MHz.

The second assumption is that the typical electric field strength for a good picture in an urban setting is around 1000- to 2000 μV/m. This is also quite reasonable and consistent with FCC and other broadcast guidelines. These guidelines increase slightly with increasing frequency to account for additional path losses.

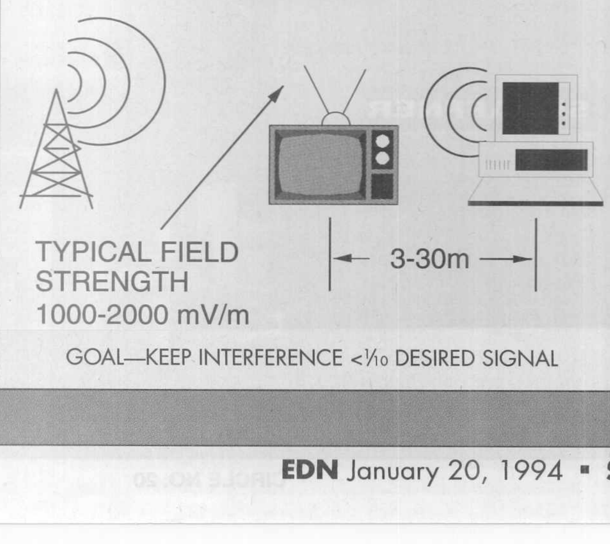
The third assumption is that a computer will be located within about 3m of a television receiver in the home and 10 to 30m away in a commercial situation. The commercial situation will also likely have a wall between the source and receiver, which provides additional shielding.

The fourth assumption is that by keeping the signal strength of the interference less than 1/10 of the desired signal strength, the interference effects will be minimal.

That's the whole basis of the FCC and VDE radiated emission limits—keep the emissions to less than 1/10 of the typical desired television receiver signal strengths. The test distances for the two test categories (Class A—30m and Class B—3m) are based on the above assumptions on distance. The intervening wall for the commercial cases provides the 10-dB relaxation of the Class A limits when the two are scaled to the same separation distance.

The increasing stair-step with frequency accommodates the increasing broadcast guidelines for desired signal strength. These regulations are really sensible engineering guidelines.

Fig A—Model for commercial radiated emission limits



limits, but you usually have no choice. *Medical devices can be a lot tougher to design than commercial products.*

EMI and the automotive market

The automotive market includes electronic equipment used under the hood and throughout vehicles for control, convenience, and comfort. (This market also includes vehicles other than automobiles such as trucks and trains.) Equipment ranges from engine controls to AM/FM radios and cellular telephones. The environment can be extremely severe, both inside and outside the vehicle, and cost sensitivities are excruciating. The cost of failure ranges from low to high, depending on function.

Automotive environments are among the toughest in the world. Just think about all the extremes in the automotive environment. Temperatures can range from subzero to boiling. Moisture, grime, and petrochemicals are constant threats. RF fields can be excessive, due to both onboard and external transmitters. Human ESD is a potential menace, and power glitches are always present. All of these problems must be dealt with at the lowest possible cost. Even a few cents of added cost per unit can add up to millions of dollars in production volumes.

The next time you're complaining about design constraints, remember your colleagues in the automotive world. And the next time you see an article or paper from the automotive world, read it with gusto as we do. We find some of the most creative EMI engineering originates in the automotive market.

Automotive EMI standards are voluntary, but rigorous. Given the tough automotive environment, you'd expect to see tough, mandatory EMI requirements. Well, they're tough all right, but voluntary. They are applied rigorously however, so they almost have the effect of mandatory regulations.

The Society of Automotive Engineers (SAE) has published a number of comprehensive standards related to automotive EMI issues. The two key ones are J551 and J1113. The first, J551, is a vehicle-level EMC standard that originally focused on radio and TV emissions, like the current FCC emission limits on computers. This standard is now undergoing review to include vehicle immunity issues as well. The second SAE standard, J1113, is the component-level EMC standard that applies to electronic modules. J1113 includes both immunity and emission tests and limits and is functionally similar to MIL-STD-461 for the military. In addition, each of the major US automotive companies (GM, Ford, Chrysler) also have their own internal EMC standards based on the SAE standards. The general goals are the same, but the specific tests vary among the companies.

Unless you're a vehicle designer, your key concern is J1113 plus applicable customer requirements. These tests

can be grueling, but they do represent the real-world environment of automobiles, trucks, and other similar vehicles. There is some relief, as immunity test levels may be grouped by "region," depending on the function and performance impacts. For example, minor upsets to convenience electronics (radio or climate control) are not held to the same standards as a major upset to an essential function (braking or steering). It's a pretty sensible approach, even if the tests are tough.

So what's the impact on design?

For automotive products, both immunity and emissions limits can have a severe impact on design. The severity of this impact is compounded by the extreme cost constraints. For emissions, the automotive component limits can be 60 dB (1000 times) more stringent than the FCC Class A limits. The objective is to prevent interference to sensitive onboard AM/FM radios that often reside only a few feet away from the interference source. Commercial design practices often don't work. Because of the low signal levels, any repetitive digital signal is a potential interference source, so in addition to clocks, you must also give some attention to repetitive address, data, and control signals. Efforts are now being made to reduce EMI at the integrated-circuit levels, and even software can be a factor (a repetitive loop can cause more EMI than just waiting for an interrupt). Any reduction in emissions, no matter how small, may be needed to meet automotive EMI emissions limits.

For immunity, the most important weapons in the war against EMI are shielding, filtering, and transient protection. Shielded cables are usually not practical because of cost and weight. Careful cable routing can affect EMI and is often used in automotive EMI control. Software can also help to make systems more noise tolerant. The problems are tough, but they do get solved.

EMI and industrial controls

The industrial-control market includes electronic equipment used to monitor and control manufacturing processes. Equipment ranges from thermocouples and µP-controlled valves to sophisticated multiloop control systems. Environments are often harsh and cost sensitivities are moderate. The cost of failure can be high, particularly for large-scale processes.

EMI regulations for industrial controls, like medical devices, are voluntary but changing. Today, industrial controls are exempt from any EMI regulations in the United States and they are need only meet emissions requirements in Europe. However, this situation is changing in Europe. The EC is mandating immunity to RF, ESD, and power disturbances on electronic equipment.

Many suppliers of industrial controls

The Designer's Guide to Electromagnetic Compatibility

have rigorous internal standards, focused on EMI immunity. These are often proprietary and are based on experience earned the hard way. Others have no standards and, as a result, often have EMI problems in the field. If you're designing industrial-control systems, you may want to investigate EMI standards with your suppliers. We've seen several cases where robust control systems were brought to their knees by unprotected (and very vulnerable) sensors and control panels.

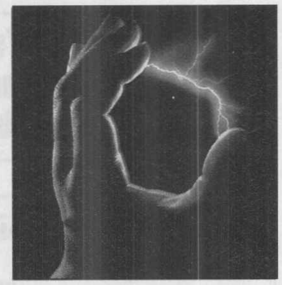
In spite of these problems, the industrial-control industry has given us some of our best directions for dealing with EMI immunity. The IEC 801 series, used by the EC for the new European regulations, were developed as voluntary standards for industrial- and process-control applications. As such, they form an excellent set of guidelines for anyone designing for the industrial-control markets.

The "big three" threats addressed by the IEC 801 series are all present in the industrial-control arena. High levels of RF energy are present, often generated by handheld radios. ESD is a constant threat from both humans and from material movement. Power disturbances are everywhere in this environment. The new EFT (electrically fast transient) test does a good job of simulating the "showering arc" of nearby relays and contactors. The key industrial-control objective is satisfactory operation in a tough environment.

So what's the impact on design?

The design requirements are similar to EC limits or to medical devices without the leakage current limitations. Immunity is the key issue, which means that you need to protect vulnerable circuits through filtering, transient protection, and shielded mechanical packaging. You may also need shielded cables and connectors. Better yet, consider fiber optics for these applications. Fiber-optic cables also help solve ground-loop problems that plague distributed control systems. EDN

That's it for the rules and regulations. We hope you enjoyed our design engineer's view, rather than the more traditional test engineer's view. We also hope that by looking at several different electronic areas, we've given you some insights into why all these EMI regulations exist and even the problems that spawned them. By understanding these problems, we can design better solutions.



ESD as an EMI problem... how to prevent and fix

There are two types of ESD (electrostatic discharge) problems with electronic systems: those encountered as you build products and those that occur after you ship products. The first is a manufacturing problem and the second is an EMI (electromagnetic interference) problem. This chapter addresses the EMI problems, ranging from equipment upset to permanent damage.

This distinction is important. We've seen cases where companies had very well-established ESD controls during production, yet their products failed in the field because of ESD. The care in manufacturing the products was not backed up by the same care in designing the products. The potential for ESD is everywhere, not just on the manufacturing floor. With good design, field ESD problems can be prevented.

One key problem with ESD is lexical: the term is ambiguous and means different things to different people. For the system user, it simply means the presence or absence of a "spark." For the manufacturing engineer, it means wrist straps and air ionizers. For the semiconductor engineer, it means conductive packaging. For the test engineer, it means ESD guns. For you, the designer, it means bulletproofing your design.

Another problem with ESD is its sheer diversity. ESD comes from multiple sources including humans, furniture, or even simple materials such as paper or plastic. ESD travels through multiple coupling paths which include circuits, grounds, and transient electromagnetic fields. ESD creates multiple failure modes including damage, upset, lockup, or latent failure. And the problems are getting worse. Today's faster circuits are more prone to upsets as they mistake ESD glitches for legitimate signals. Today's smaller devices are also more prone to damage because they can no longer safely dissipate the ESD energy.

In this chapter, we'll focus on how to prevent and fix ESD problems at the design level. First we'll look at the ESD phenomena and failure modes. Then we'll give you some ESD design guidelines. We'll start from the inside of your design and work out—circuits, cables/connectors, grounding, shielding, and packaging. We'll even touch on software, a crucial last stand against ESD as an EMI problem.

The term "electrostatic discharge" is ambiguous... it can mean different things to different people.

A quick look at the ESD phenomena

An ESD event starts with a very slow buildup of energy (often taking tens of seconds), followed by a very rapid breakdown (typically in the nanoseconds). It's this fast breakdown that causes so many EMI problems in modern electronic equipment. With typical pulse rise times in the nanosecond range, the energy discharge yields equivalent EMI frequencies in the hundreds of megahertz. Due to its high speed and frequency, ESD energy can damage circuits, bounce grounds, and even cause upsets through electromagnetic coupling.

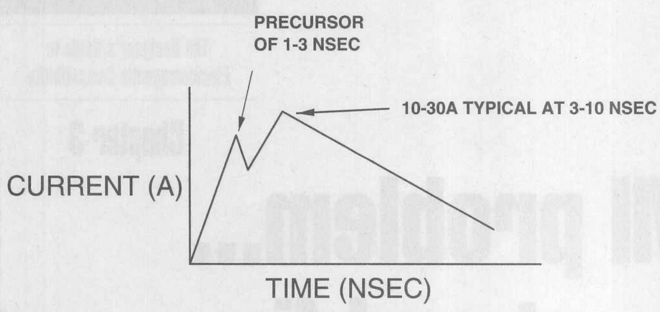
You really have only two choices when dealing with ESD. You can prevent it or you can deal with it. Prevention is the primary strategy in manufacturing, because even a single ESD event can damage vulnerable circuits or boards. You usually cannot rely on prevention for equipment in the field. Sooner or later, a discharge will occur. As a designer, you must deal with ESD and the adverse effects of an ESD event on your equipment. Fortunately, with a little care, you can greatly decrease your vulnerability to this threat.

Predischarge vs postdischarge

We like to divide ESD into two phases, predischarge and postdischarge. In the predischarge stage, we focus on *charge buildup*. In the postdischarge stage, we focus on *charge breakdown*. As designers, our primary interest is on the postdischarge stage, but it helps if we understand how the problem starts in the first place.

Most of us are familiar with ESD generation. The most common method is triboelectric charging, caused by stripping electrons from one object (resulting in a positive charge) and depositing these electrons on another object (resulting in a negative charge). In a conductor, charges recombine almost instantly while in an insulator, the charges can remain separated. In an insulator, it may be a long time before

Fig 1—Typical ESD waveform



significant charge recombination occurs and, consequently, a voltage builds. If the voltage becomes large enough, a rapid breakdown occurs through the air, creating the familiar ESD arc or spark.

Typical sources of triboelectric charging include humans, furniture, and material or device movement. Although ESD in manufacturing is concerned with all three, our main concern as equipment designers is with human discharge, because it's most likely that humans will be the source of our ESD problems. Because few of us can control how and where our products will be used, we must assume that *ESD will occur.*

Typical ESD levels

A lot of research has gone into ESD in recent years, and there is still much to be learned. **Fig 1** shows some typical ESD waveforms based on recent human body models. **Fig 2** shows the equivalent circuit of a human. Peak currents can exceed tens of amperes, and rise times are in the nanosecond range. The initial spike, or precursor, assumes that the human body has distributed capacitance (most in the body, some in the arm) rather than simple lumped capacitance. Actually, the need for this distributed approach has only been recently recognized, and it accounts for some anomalies in ESD testing. More recent research indicates that additional faster, small precursors also exist, because of distributed capacitance in the fingers. Where will it end? It's hard to say. So far, every time someone develops a method to measure faster speeds, they see faster precursors. It may be that we still haven't reached the limits on this question.

The waveform in **Fig 1** show current rather than voltage because current, not voltage, is more likely to cause problems. It's like a burst dam—it's the water flow that does all the damage, not the pressure that was behind the dam before it burst. The voltage is merely a convenient metric of the electrostatic "pressure" before the ESD event occurs. When dealing with ESD as a design problem, you need to think in terms of current flow, not voltage.

In addition to current, the ESD rise time is also important. Remember, ESD is a very fast transient, so two parameters are important: peak level and rate of change (dI/dt). In the EMI world, we often convert rise times to an equivalent EMI frequency.

$$F = 1/(\pi t_r)$$

where t_r = rise time. There's really nothing magic here. The equation is based on the Fourier transform, as shown in **Fig 3.** (This equation also tells you the bandwidth needed in a oscilloscope to look at transients or edge rates.) With a typical 1-nsec rise time, the equivalent ESD frequency is over 300 MHz. This is no longer just static electricity, and you must use VHF (not dc) design techniques to prevent problems.

Effects of humidity and resistance

We all know that the lower the humidity, the higher the likelihood of ESD problems. Humidity helps because moisture reduces surface impedance and allows charges to recombine at a faster rate. Static-dissipative materials, which also provide a lower surface impedance on materials such as countertops or packing material, create the same effect.

It is more difficult to develop the high voltage necessary for an ESD breakdown in materials that continuously dissipate charge buildups. In fact, studies have shown that above 50% humidity, it's very difficult for human discharges to exceed about 2000V. But at 5% humidity, ESD levels can exceed 15,000V.

So, humidity doesn't really control ESD, it just prevents high voltage levels from occurring in the first place. By the way, it's easy to get fooled here. We saw one case where a million-dollar production line was crashing and everyone insisted it couldn't be ESD because of the high humidity levels.

Fig 2—Equivalent ESD circuit of a human

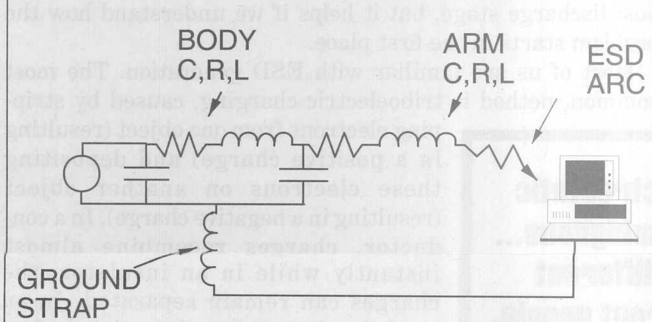
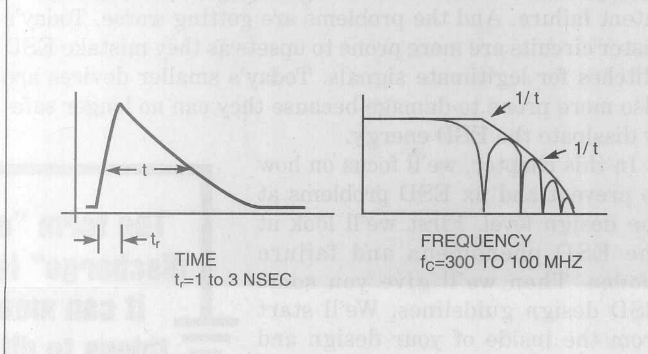


Fig 3—Time vs frequency for ESD



Besides, no one ever got zapped by ESD sparks. It turned out that the production line's control panel was vulnerable to levels as low as 1500V, which is well below the threshold of human feeling (about 2000-3000V). Once properly diagnosed, the problem was easy to fix.

ESD has multiple failure modes

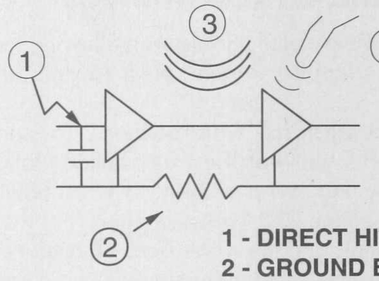
One thing that makes ESD so frustrating is that it has several failure modes, which are not completely independent. Solve one problem and another pops up. But once you understand the different modes, the problems make more sense and become easier to solve. **Fig 4** shows four ESD failure modes. We've run into all four at one time or another. In several cases, more than one failure mode was active. That kept the troubleshooting phase interesting, to say the least.

The first failure mode is upset or damage caused by ESD current flowing directly through a vulnerable circuit. This situation is identical to manufacturing's ESD concerns; any current injected into a pin is likely to damage a device. Consequently, we don't like to see direct connections such as a connector or keyboard to any IC from the outside world. Even a small amount of series resistance or shunt capacitance in these circuits can limit the current through the IC to safe levels.

The second ESD failure mode is upset or damage caused by ESD current flowing in the circuit ground. This problem can be sneaky because most designers assume that the circuit ground has a low impedance. But with 1-nsec rise times (300+ MHz), the ground impedance may not be low at all and the ground will "bounce." The usual result is an upset, but ground bounce can also drive CMOS circuits into latch-up. Latch-up is a case where the ESD doesn't actually do the damage; it just sets things up so that the power supply can destroy the part.

The third failure mode is upset caused by electromagnetic field coupling. This effect usually doesn't cause damage because only a small fraction of the ESD energy is typically coupled into the vulnerable circuit. This failure mode depends heavily on the rise time (dI/dt), circuit loop areas, and presence or absence of shielding. This effect is often called the *indirect coupling mode.* Incidentally, electromagnetic field sources don't need to be very close to cause problems for a sensitive circuit. We've seen several failures from ESD-generated electromagnetic fields 15 to 20 ft away.

Fig 4—Four ESD failures



1 - DIRECT HIT ON CIRCUIT INPUT
2 - GROUND BOUNCE
3 - ELECTROMAGNETIC FIELD
4 - PREDISCHARGE ELECTRIC FIELD

The fourth failure mode is caused by the predischarge electric field. This failure mode is not as common, although we've seen it several times with very sensitive, high-impedance analog circuits. We've yet to see it cause a problem with digital circuits although with decreasing circuit geometries, it's probably just a matter of time.

Because of ESD's transient nature, fast digital circuits are more prone to ESD upset than are slow analog circuits. In fact, ESD rarely upsets analog circuits. (Of course, both analog and digital circuits are vulnerable to ESD damage from direct discharge through the circuit.) Digital circuits with edge rates faster than 3 nsec are particularly vulnerable because they can be fooled by phantom ESD pulses. Consequently, today's digital circuits are more vulnerable than older circuits that had slower edge rates. *The window of susceptibility is now wide open to ESD.*

For the remainder of this chapter, we'll look at design techniques to control and prevent common ESD problems. We'll look specifically at how to bulletproof your design against ESD.

Two strategic concepts...

The first ESD strategy we recommend is to determine the potential first points of contact. These are the most likely points for ESD hits to occur. Vulnerable points include the obvious—such as keyboards, switches, and indicators—and the less obvious—such as printer or communications ports. In these cases, the contacts may not be from people but from the cable to the connector pins. Don't forget other nonobvious points such as locks on personal computers. Anything metal is suspect, especially those with electrical connections.

The game plan here is to divert or limit the energy. You should try to divert ESD currents away from vulnerable circuit inputs using filters or transient suppressors. Limit ESD currents with small resistors or ferrites whenever possible. Better to dissipate ESD energy in a resistor than in an integrated circuit.

The second ESD strategy we recommend is to determine the most vulnerable internal circuits. These are the circuits most likely to be upset by electromagnetic effects and include resets, interrupts, and critical control lines.

The game plan here is to limit the amount of electromagnetic field coupling and ground bounce. Use filters to protect these critical circuits individually. Use cable or cabinet shielding to protect circuits collectively. Pay particular attention to ribbon cables. They are efficient antennas at the equivalent ESD frequencies of over 300 MHz.

Protection at the circuit level

Good ESD protection begins at the circuit level. We like to see transient protection or filters on all external lines, plus filters on the critical internal lines. In no case should there be a direct connection from an integrated circuit to an exposed external point. That's like hooking a lightning rod to your system. **Fig 5** shows a summary of our ESD-protecting circuit recommendations.

Transient protection devices must be fast enough to act on the ESD. This rules out slow devices such as lightning

The water balloon: an ESD analogy

We've all been trained to view electricity like water flowing through pipes. Voltage is the pressure and current is the water itself. All neat and clean, if you'll pardon the pun.

We see ESD as being the electrical "water balloon." You can pass it back and forth (transfer charge), and if you watch a water balloon fall from the top of a building, you can even say you saw a package of water flowing by you.

The problem occurs when the ESD "water balloon" hits the ground. There is a quick splash (fast rise time), and the water goes all over the place. It's tough to predict, and tough to repeat in a precise manner. And it can be just as tough to control.

arrestors. Typical lightning transients are in the 1- to 10-μsec range, or over 1000 times slower than ESD transients.

The best ESD protection devices are silicon based such as zener diodes or General Semiconductor's Tranzorbs. We prefer the Tranzorbs because they have a larger die area. They are specifically designed to act quickly and dissipate a lot of energy for their size. Standard power-line MOVs (metal oxide varistors) are marginal for ESD although the new, multilayer devices are faster and should work well for ESD protection. Standard arc devices are generally too slow for ESD, although vendors of some small gas tubes claim that their products are fast enough.

For any of these protection devices to reach their full potential, you must keep their leads short. A few centimeters of lead length will degrade even the best device's protection. As a rule of thumb, component leads have an inductance of about 10 nH/cm. A typical 15A ESD pulse with a 1-nsec rise time will produce 200V across a 2-cm piece of wire. This means a device that clamps at 100V could actually allow 300V to be impressed across the input if each of its leads are 1 cm long. You can shorten the leads on a board with transmission methods rather than stubs (**Fig 6**). **The objective is to put a momentary "RF short" across the protected lines.**

We simply cannot overemphasize this point—we've seen too many ESD problems that were aggravated by excessive lead lengths.

You can also use high-frequency filters for ESD protection. While transient protectors act at a fixed threshold level, filters reduce all ESD transients by a proportional amount. Like the transient protectors, you'll need high frequency performance, so keep the leads short. You should have at least 40 dB of attenuation at 100 to 300 MHz to have an appreciable effect on ESD transients.

Ground your transient protectors or filters to the case, not the circuit ground. Remember, an ESD pulse can reach tens of amps; if you dump that large current directly into your circuit ground, it will very likely bounce. As an alternative, you can add some series impedance to the protected lines by using a small resistor (50 to 100Ω) or ferrite bead. This will limit the current and may let you get away with using the circuit ground. It's still better to use the chassis as the ESD protection ground if at all possible. Remember, we're trying to divert the energy away from both the circuit and its ground paths. Once ESD currents get onto your board, you are in trouble.

Ferrites are your friends for ESD. We find that ferrites are like penicillin for ESD problems. The materials are very lossy in the 100 to 500 MHz range, so they act like resistors against ESD. (Small ferrite beads look like 50 to 100Ω at 100 MHz). The advantage is that at low frequencies, beads look like very small inductors, so they become transparent on most digital lines. Because of their low impedance, however, you can't use them on a high-impedance input. For high-impedance inputs, use ferrites with a 100 to 1000 pF capacitor to provide a low shunt impedance at high frequencies. The rule is: high series impedance, low shunt impedance.

A word of caution about ferrites: be sure to use EMI ferrites. We had one case where we recommended ferrites and the designer installed beads designed for low loss at high frequency. That's fine if you want high efficiency, such as with pulse transformers, but when dealing with EMI, we'd rather turn the EMI or ESD energy into heat. So stick with the EMI ferrites for the best ESD results.

Multilayer pc boards can be 10 to 100

Fig 5—ESD circuit recommendations

Transient protection devices
- Must be fast enough for ESD
- Keep leads short

High-frequency filters
- Must have attenuation at 100- to 300-MHz range

Ferrites
- Ferrites are your friends for ESD

Multilayer boards
- Ten times harder against EM fields

Protect key circuits
- Resets
- *Interrupts*
- Critical control lines

Fig 6—ESD transient protection

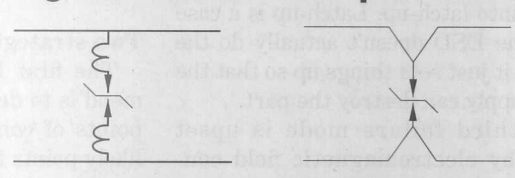
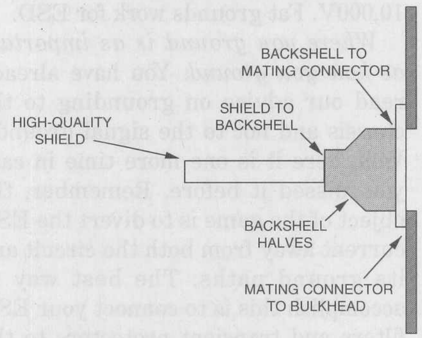


Fig 7—ESD proofing cables & connectors



times better than a 2-layer board for protection against the electromagnetic fields of indirect ESD. This observation also holds true for other field effects such as emissions or RF immunity. We've seen these improvements with multilayer boards many times, and believe us, they really make a big difference for ESD and RFI.

The ground planes on multilayer circuit boards achieve these improvements by reducing the "loop areas" that act as ESD receiving antennas. At high frequencies, ESD induces opposing currents in the nearby copper plane, which cancels the fields ESD induces in the trace. In essence, the proximity of ground planes turns traces into transmission lines instead of antennas. The traces are therefore much less efficient in intercepting electromagnetic fields. The lower ground impedance provided by ground planes also reduces ground bounce, a second desirable effect.

Incidentally, you don't need both a power and ground plane for this effect to work. The miracle occurs with the addition of the first plane. The real secret is to get the plane as close to the traces as possible so that the cancellation can work. We've added ground planes to 2-layer boards using copper tape and have seen substantial improvements. Connecting circuit grounds to the ground plane works better, but it's not absolutely necessary. We'll look at this again in more detail in the chapter on circuit boards.

Protecting key circuits is our final piece of advice at the circuit level. It's really quite simple, but often overlooked. We've solved several ESD problems just by adding a small RC network to a microprocessor's reset line. Be sure to follow the manufacturer's recommendations on reset lines. We had one case where the designer left out a recommended RC network because he didn't want to slow down the system. Adding the RC network solved his ESD problems. You should pay attention to interrupt lines and critical control lines that could be upset by a glitch in addition to resets.

Protection at connector and cable

Cables and connectors are critical elements of ESD control. Cables act as both unintended antennas and unintended conductors for ESD energy. You must address them any time ESD is a threat. Furthermore, poor connectors can impair the effectiveness of even the best cable, so always consider the cable and connectors together as a system. Here are some design guidelines for ESD hardening your cables and connectors (**Fig 7**).

Use only high-quality cables and connectors for external cables. Remember, you're dealing with a 300-MHz threat. For external cables, we prefer shielded cables and metal or metal-plated connectors. We use either braid-over-foil or high-coverage braid cable shielding. While foil alone provides good shielding, if the foil splits you lose all your shielding. The shield must have a full circumferential bond to the connectors—use absolutely no pigtails or drain wires for ESD control! The metal cable connector must mate with a metal chassis connector (please, no plastic).

The objective is to provide full 360° coverage all the way from the cable shield to the chassis. Try to make the connection water tight, too. A tight electrical bond between cable shield and connector diverts any ESD currents, radiated or conducted, away from the wires inside the cable and prevents sneak coupling to the inner wires through the shield-to-wire capacitance.

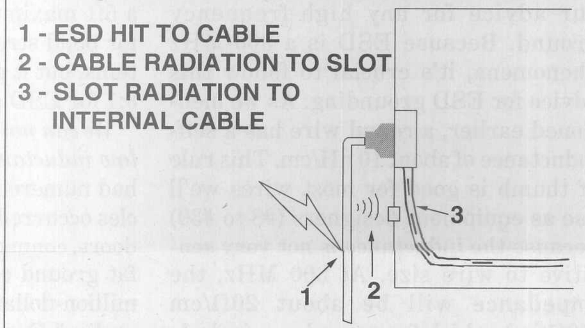
If you can't shield, then filter. If you can't shield the external cables, then you must provide filtering or transient protection on all signal lines including signal grounds. As we discussed earlier in the circuit section, keep the leads short and connect the filters or transient protectors to the chassis, not the circuit ground. If you must connect to the circuit ground, then you must add series resistance (ferrites or small resistors) to limit the ESD current.

Don't forget your internal cables. You can relax your guard a bit on internal cables, particularly if you use a shielded enclosure. Be careful with cable routing, and keep internal cables away from seams and slots in your enclosures. ESD jumps through seams and slots and can also generate very intense local electromagnetic fields through "slot antenna" effects. Keep your internal cables at least an two inches away from these areas (**Fig 8**).

If your enclosure is unshielded, then you must pay more attention to your internal cables. While they may not be exposed to direct hits like the external cables, they still can be very vulnerable to ESD-radiated effects. We've found common-mode ferrites (one ferrite over the entire cable) to be very effective at solving ESD problems with internal cables.

If you're using ribbon cables, maximize the number of ground returns and spread them out through the cable. These steps minimize "loop area," which reduces radiated pickup in signal lines. Ideally, allocate a ground return line for every signal line, but most of us can't afford that. At a minimum, strive for a 5:1 ratio between signal and return lines with the returns evenly distributed through the cable. This

Fig 8—Potential ESD disaster



Predicting the voltage induced by an ESD electromagnetic field

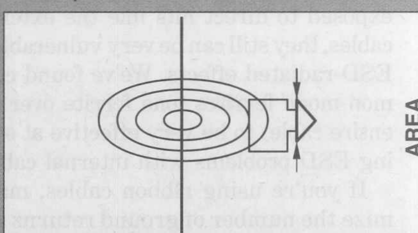
You do not need a direct ESD hit to your equipment to cause problems. Fast ESD rise times can develop significant electromagnetic fields which irradiate you equipment much like a nearby radio transmitter. Although short in duration, these fields are often intense enough to cause mysterious malfunctions. We've seen this effect up to 20 ft away on several occasions.

A quick review of some basic physics shows why this is possible. By using Faraday's Law and some simple assumptions, we can show that ESD can induce transients of several volts in nearby electronics equipment due to ESD. Here's the derivation:

(1) $V = N d\phi/dt$
(2) $\phi = BA$ and $d\phi/dt = A(dB/dt)$
(3) $B = \mu I/2L$ and $dB/dt = (\mu/2\pi L)(dI/dt)$
(4) Then $V = (NA\mu/2\pi L)(dI/dt)$

Assume that N = 1 turn
A = area of loop
L = distance from loop
dI = 10A
dt = 1 nsec

Fig A shows a simple configuration, with induced voltages for several values of area and distance. From these figures, it's easy to see why radiated ESD can cause problems.



INDUCED VOLTAGE

AREA \ DISTANCE	10 cm	1m	3m
1 sq cm	2	0.2	0.07
10 sq cm	20	2.0	0.70

Fig A—An example of ESD field coupling.

scheme separates every signal line from a return line by no more than two intervening wires. In addition, flat clamp-on ferrites are very effective for ESD protection on ribbon cables.

Some ESD grounding guidelines

Keep them short, flat, and fat. That's our advice for any high-frequency ground. Because ESD is a 300-MHz phenomena, it's crucial to follow this advice for ESD grounding. As we mentioned earlier, a round wire has a self-inductance of about 10 nH/cm. This rule of thumb is good for most wires we'll use as equipment designers (#8 to #30) because the inductance is not very sensitive to wire size. At 300 MHz, the impedance will be about 20Ω/cm (50Ω/in.), which far exceeds a wire's dc resistance. At high frequencies, ground inductance is a real show stopper.

One way to reduce inductance is to use a wide strap, rather than a wire. The trick is to keep the aspect ratio (length-to-width) as low as possible. In short, the fatter the better. For many years, the military has suggested using a 5:1 maximum ratio (length-to-width) for bond straps in radio and radar systems, but it prefers to see no more than 3:1 for ESD grounds.

We can not overemphasize this need for low inductance grounds for ESD. We've had numerous cases where major miracles occurred by simply bonding chassis, doors, connectors, and cable shields with fat ground connections. Remember the million-dollar production line discussed earlier? Four pieces of 1-in. copper tape used to improve a high-frequency ground raised the ESD vulnerability of that system from about 1500V to over 10,000V. Fat grounds work for ESD.

Where you ground is as important as how you ground. You have already read our advice on grounding to the chassis and not to the signal grounds. Well, here it is one more time in case you missed it before. Remember, the object of the game is to divert the ESD current away from both the circuit and its ground paths. The best way to accomplish this is to connect your ESD filters and transient protectors to the chassis, not the signal ground.

What if you don't have a chassis ground? Then limit the current with resistors or ferrites, which works most of the time. In a pinch, adding a separate metal plate for the ESD ground can be effective. This has been used for years in large systems and is known as a "transient plate." The plate diverts the ESD current away from the circuit and acts as a "free space" capacitor.

Don't overlook "soft" grounds for ESD. Here is one final grounding concept for ESD. You may want to limit the current in an ESD ground path with resistance. Wrist straps and conductive mats are good examples of this technique. Both include series resistance to limit currents. While the prime reason for using current-limiting resistance in ground paths is for 60-Hz safety, you can also use it as an effective ESD countermeasure.

As an example, we had a case where discharging an ESD gun to a computer's integral "touch-me" panel would crash the system. The idea was to have the operator discharge to the touch-me panel to lower the number of nuisance failures. (A complete ESD redesign was out of the question.) Unfortunately, the cure was worse than the problem. But then a light went on...why not add a series resistor to the touch me panel? Sure enough, a 1000Ω carbon resistor had a low enough resistance to provide a discharge path, yet the resistance was high enough to limit the ESD current to a safe level. Case closed.

Some ESD shielding guidelines

By now, you're well aware of the need for shielding to protect against ESD's electromagnetic field effects. But how

much is needed, and what are the problem areas?

Thin shielding material works fine. Because ESD fields are high-frequency fields, thin conductive materials provide high shielding levels. For example, aluminum foil provides over 100-dB of attenuation at 300 MHz, which is more than adequate for most ESD problems. (Generally, 20 to 40 dB is good enough for ESD protection.) Thin metal coatings (such as nickel paints) provide at least 40 dB in this frequency range and other metal-application techniques (such as vacuum plating or electroless deposition) are usually good for 80 dB of protection or more.

Slots and seams destroy ESD shielding. The real problem with ESD shielding is leakage through discontinuities such as slots and seams. A rule of thumb in the EMI world is to limit the longest dimension of any opening to 1/20 of a wavelength at the highest frequency of concern. For an ESD frequency of 300 MHz, this means slots or seams must be less than 5 cm (about 2 in.). Even 2 in. may be too long because an opening this size only provides 20 dB of attenuation through the slot.

Unfiltered penetrations also destroy shielding. If you follow our advice on filtering or shielding all external connections, you shouldn't have a problem. If you don't follow the advice, then watch out for any shield penetration. Holes in your shield will carry ESD energy into the cabinet as if it was on a superhighway.

Here's our advice for ESD shielding.

- Use a continuous metallic coating where possible with minimal seams.
- Filter or shield all penetrations to the shield.
- Keep the longest dimension of any opening less than two inches, and keep all cables and circuits at least two inches away from any of these openings.
- If you still have shielding problems, seal the slots and seams with conductive gasket.

We'll cover shielding and packaging in more detail in Chapter 7.

Don't forget your software

If all else fails and your system is still upset by ESD, your *software* may be able to rescue you. Obviously, this won't work on ESD damage nor will it work on systems without a computer or μP. But with even a few lines of code, you can change an ESD disaster into an ESD success. These same software techniques also work well on other EMI sources.

We strongly advocate including noise-tolerant software in any system. You should write your software assuming that sooner or later ESD will upset your system, and that some type of recovery will be needed.

We've seen several cases where software saved the day. The first case was in the mid-1980s and involved a brand new piece of factory automation equip-

Key points

ESD is an extremely fast transient
- 1- to 3-nsec rise time
- Equivalent frequency of 100 to 300 MHz
- Tens of amps

ESD has multiple failure modes
- Direct hit to circuit
- Ground bounce
- Electromagnetic fields
- Predischarge electric field

Two strategic concepts
- Determine first point of human contact
- Determine most vulnerable circuits

Two design tactics
- Limit energy
- Divert energy

ESD circuit protection
- Transient devices, filters, ferrites
- Multilayer boards

ESD cable protection
- High-quality shields and connectors
- Full circumferential connectors

ESD grounds
- Keep length-to-width less than 3:1

ESD shielding
- Thin materials adequate
- Pay attention to slots and penetrations

Software
- Design in noise tolerance against ESD spikes

ment. Or more precisely, about 50 brand new units. This product was the company's first µP-based system and it had many new features. Unfortunately, it also was very sensitive to almost any EMI noise. About 50 of those new units had been returned by unhappy customers. Not a pretty sight.

The pressure was on and the company needed an EMI miracle. One key symptom was that the unit did not reset, it just became lost. A quick look showed several unused and unterminated interrupt lines. That clue led us to the software. Sure enough, these unused interrupts had no software protection, so any noise that triggered an interrupt sent the system out to lunch. The miracle solution—add a return-from-interrupt instruction in all the unused interrupt-vector locations. Even though the product still had potential EMI problems, this solved the immediate problem and let the customer ship products.

The key is to plan for the unexpected and when it occurs be able to recognize the problem and recover. Your goal is graceful degradation, not system lockup or disaster. ESD can flip any bit in memory, resulting in program-flow or data errors. ESD can also corrupt data on I/O lines and buses. At a minimum, we like to see "Return" instructions in unused interrupt locations; memory parity

checking; and type and range checking on I/O data. Simple checksums in critical data tables and self-monitoring programs also help. Add in some simple hardware, such as a watchdog timer and error-correcting memory, and you've gone a long way toward bulletproofing your software against ESD.

Quick comments on ESD testing

This series focuses on design, not regulations and tests. Nevertheless, you may have some questions on ESD testing, so here are some quick comments.

Presently, there are two key standards for ESD testing. The first is IEC 801.2 (International Electrotechnical Commission), which has been incorporated in the EC EMI requirements. If you are designing equipment for sale in Europe, this is the standard to meet. The second standard is ANSI C63.16 which is a voluntary standard still in draft form. This is not an international standard and meeting it does not satisfy any regulations. It may interest you, however, if you are designing consumer products for markets other than Europe. This procedure uses a statistical approach rather than an absolute pass/fail approach that may be better suited for products that can tolerate nuisance failures.

Both of these standards describe test methods and both make recommendations for test levels. Neither standard tells you the precise ESD levels to meet and neither tells you specific error criteria. You still need to decide just how to apply these test specifications to your equipment. You can do this through a test plan or test procedure that you develop.

Here are our test preferences and recommendations, although you may have good reason to use different methods with your equipment.

- We prefer IEC 801.2, simply because it is more widely accepted and it's a more mature document.
- We prefer the "contact" test method over the 'air discharge' method, because it is more repeatable.
- We recommend doing both the "indirect" and the "direct" tests, regardless of whether your unit is shielded or not. Both types of problems exist in the real world, and you should test for both of them.
- Finally, we recommend that you have a test plan in place before you begin—creating one at the test lab is too late. EDN

That's it for ESD as an EMI issue. We hope you enjoyed our focus on ESD design, rather than ESD test. You've seen that ESD can be generated in multiple ways, and that ESD has multiple failure modes. You've also seen that there are multiple design solutions as well.

The Designer's Guide to Electromagnetic Compatibility

Chapter 4

Radio-frequency interference... why computers and radios hate each other

RFI (radio-frequency interference) is a serious EMI threat to all modern electronic systems. This is largely due to the sheer proliferation of radio transmitters. These radio transmitters range from large, high-power transmitters (broadcast, communications, radar) to small, low-power equipment (handheld radios, cellular telephones). It's not always the big guys that cause problems—a handheld radio three feet away is a much bigger threat than the broadcast station a mile away.

At the same time, radio and television receivers are very vulnerable to RFI pollution from nearby computers. After all, a communications receiver is supposed to find very small amounts of power in a very crowded RF spectrum and then turn that energy into usable information (television, communications, telemetry, radar image, and so on). It's a tough job, and the microprocessor explosion made it even worse. Every digital system is an unintended transmitter (thanks to the clocks) connected to an unintended antenna (thanks to wires and cables). The net result is a lot of unintended RF energy jamming the airwaves.

In this chapter, we'll look at both problems, but from the perspective of the electronic-equipment designer, not the RF design expert. We will, however, borrow a lot of ideas from the RF design world. After all, they've been working on RFI problems ever since Marconi's time. Our focus will be on how to design non-RF products to live in an RF-intensive world.

Radios and computers...mutual antagonists

Several years ago, we presented two papers at a conference titled *Radios and Computers—Mutual Antagonists, Parts I and II.* One of these papers addressed computers as the source, and the other addressed computers as the victim. Or in more technical terms, one addressed the issue of emissions; the other addressed the issue of immunity or susceptibility.

If digital signal levels are high enough, nearby communications receivers can be rendered unusable.

We presented the papers back to back, and it was actually a bit of fun. We each gleefully pointed the finger at each other, blaming the other guy for our problems. But then we got serious, because we were discussing real-world problems and how we had dealt with them. Or, as we like to say "It may be somebody else's fault, but it's still *our problem.*" Let's look at both sides of the RFI problem in more detail.

Digital emissions: computers as a threat

Every computer is a potential RF polluter. Repetitive digital signals are rich with harmonics that can extend well into the GHz range. This unwanted energy can be radiated, using cables and wiring as antennas, or it can be conducted through the ac power system. If the levels are high enough, nearby communications receivers can be rendered unusable.

It was this emissions problem that caused governments around the world to pass EMI regulations. But governments are driven by complaints (or votes), so it's the squeaky wheel that gets the grease. The biggest source of complaints for this type of interference comes from the public, generally when television reception is disrupted. These complaints grew exponentially in the mid 1970s due to the microprocessor revolution. These complaints drove the Federal Communications Commission (FCC) to initiate mandatory EMI testing of personal and commercial computers in the early 1980s. These rules were patterned after regulations already in place in West Germany, administered by the Verband Deutscher Electrotechniker (VDE). Later the Japanese got into the act, and most recently the EC became involved through the CISPR 22 standard.

All of these emissions regulations have one thing in common—they aim to prevent interference to a nearby tele-

vision or broadcast radio receiver, and nothing more. While these regulations work most of the time, there are times where these limits are not good enough. For example, they are not adequate to protect nearby sensitive communications receivers such as military radios. That's why the military emission limits are about 30 times tougher than the commercial limits. Nor are they adequate to protect automobile radios, which is why automotive companies have their own limits, which are about 1000 times tougher than commercial limits.

The bottom line: commercial emission limits may not be adequate for your applications. We've worked on several projects where lax limits caused a serious problem. In one case, the emissions from a microprocessor-based control system was jamming a VHF land-mobile radio that was also a part of the system. In another case, a commercial product was widely used in fringe TV reception areas and was interfering with the weak TV signals. In both cases, the products met the FCC limits but were still causing problems. We had to establish new limits (or design goals) to control the emissions to a suitable level.

We'll emphasize this again later when we discuss RFI design techniques. We'll try to give you some guidance on ordinary versus extraordinary techniques for controlling unwanted RF emissions.

Immunity

Every electronic system is a potential victim of RF energy from nearby transmitters. Solid-state systems are particularly vulnerable to this threat because even relatively small induced voltages can overwhelm the system. The problem is increasing with the proliferation of radio transmitters, from cellular phones to satellite links. As a designer, you can't control this environment, so you must design for it.

If you're a military designer, you're already well aware of the problem, because almost all military systems require RF susceptibility tests. If you're an automotive-electronics designer, you're also well aware of the problems, because you also face a tough set of tests. Many other designers are just beginning to see this problem, either as a requirement or as a real-world problem. The US Food and Drug Administration is getting into the act for medical devices, and by 1996, RF immunity will be mandatory in the EC for virtually all electronic systems.

What are typical failure levels? As a rule of thumb, today's unprotected electronics systems typically fail at electric field levels in the 1-10V/m range. Unfortunately, today's typical environment has field levels between 0.1 and 100V/m, so problems can and do occur (**Fig 1**). Fortunately, the higher-level fields only occur close to transmitting antennas, and they are fairly easy to predict or measure.

Incidentally, there are two common metrics for RF immunity: power density (mW/cm^2) and electric-field intensity (V/m). Power density is popular in the communications industry; electric-field intensity is preferred in the EMI community. As EMI engineers, we prefer electric-field units. If you need some help on this, see **Fig 2** for conversion factors.

Electric-field intensity is a function of transmitter power, antenna gain, and distance. We use a simple formula for a quick worst-case prediction:

$$E=5.5\sqrt{(P)}/d$$

where E=V/m, P=effective radiated power in W, and d=distance from the antenna in meters. For example, a 1W transmitter at 1m yields 5.5 V/m (which could mean trouble), while a 10,000W transmitter at 1 km is already down to 0.55 V/m. It's clear that the small transmitter nearby is often a bigger threat than the distant transmitter. **Fig 3** tabulates some examples.

What about failure modes?

Analog circuits are usually much more vulnerable to RF energy than digital circuits. Most analog circuits operate at lower signal levels and are more easily overwhelmed by high RF levels. Digital circuits, on the other hand, are usually more vulnerable to ESD, power glitches, and other spikes that generate false pulses. At high enough levels, digital circuits will also succumb to RF energy.

Analog circuits are also very prone to rectification, so any modulation on the RF is "detected" and then amplified by subsequent stages. This is why you hear can hear the voice from the 27-MHz CB radio on telephone or audio amplifier operating in the kHz, not MHz, range. As a result, you must block RF energy before it gets to the first sensitive analog stage. Don't forget this piece of advice. **Fig 4** illustrates the problem; **Fig 5** shows some solutions.

RFI prevention techniques

For the remainder of this chapter, we'll look at design techniques to control and prevent common RFI problems—both emissions and immunity. Some of these techniques duplicate the ESD-control techniques described in the previous chapter. But

Fig 1—Typical RF field levels

Commercial: 1 to 10V/m
Automotive: 20 to 200V/m
Military: 1 to 200V/m
Industrial: 1 to 10V/m
Medical: 3 to 400V/m

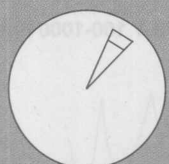
Fig 2—Power density vs electric-field strength

EMI engineers use *electric-field strength* (volts/meter, $\mu v/m$) as the parameter of choice for electromagnetic fields, while communications engineers use *power density* (watts/square meter, mW/cm^2). Here are some handy conversions:

$E(V/m)=61.4\sqrt{P\ (mW/cm^2)}$ (Far field-377 Ω)

100V/m=2.65 mW/cm^2	10 mW/cm^2=194V/m
10V/m=26 $\mu W/cm^2$	1 mW/cm^2=61V/m
1V/m=0.26 $\mu W/cm^2$	0.1 mW/cm^2=1.9V/m

Fig 3—Electric-field levels vary as power, distance, and gain



Typical values

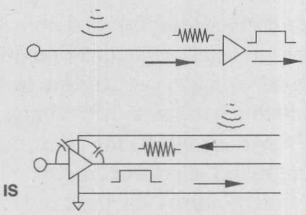
	1W	10W	100W	1000W
1m	5.000	15.000	55.00	150.00
10m	0.500	1.500	5.50	15.00
100m	0.050	0.150	0.55	1.50
1 km	0.005	0.015	0.05	0.15

$E(V/m)=5.5\sqrt{PA}/d$
P=watts
A=antenna gain
d=distance, meters

Fig 4—RF in analog circuits

INPUTS PICK UP HIGH-FREQUENCY ENERGY ON SIGNAL LINE, WHICH IS DETECTED BY THE AMPLIFIER

OUTPUT DRIVERS CAN BE JAMMED TOO: ENERGY COUPLES BACK TO INPUT VIA V_{CC} OR SIGNAL LINE AND IS THEN DETECTED AND AMPLIFIED.



nothing says one technique shouldn't fix more than one problem. That's just good EMI design.

Two strategic concepts

The first concept is to treat all cables as antennas. Because cables usually have the largest physical dimensions in a system, they are the most efficient at radiating or intercepting electromagnetic energy. As a rule of thumb, we generally assume any conductor that is over 1/20 of a wavelength is an effective antenna. (At 100 MHz, this dimension is 15 cm, or about six inches.) Of course, at 1/4 wavelength or longer, cables become very efficient antennas. **Fig 6** illustrates this critical relationship between cable length and frequency.

Don't ever assume that a shielded cable won't radiate. It's very common for high-frequency current to be coupled onto the shield, causing the entire cable shield to behave as an antenna. In fact, this "common mode" cable radiation is a key reason for failing radiated emissions tests. **Fig 7** shows an example of cable radiation, complete with a "matching network" formed by a cable pigtail. That's why we despise pigtails on cable shields—they cause serious RF problems.

The second concept is to determine the most critical circuits. These are the circuits that act as transmitters or receivers, to use an obvious analogy. The most powerful transmitters are highly repetitive signals such as clocks or address strobes. The most vulnerable receivers are analog circuits and input/output (I/O) circuits. In both cases, special attention should be given to these critical circuits.

Protection at circuit level

Good RFI protection begins at the circuit level. We like to see filters or decoupling on all external lines, plus filters on critical internal lines. We also like to see the liberal use of ferrites and multilayer circuit boards when RFI is an issue.

High-frequency filters are your first line of defense in any RFI problem. The objective here is to electrically isolate key source or receptor circuits (unintended transmitters and receivers) from the cables (unintended antennas). In general, transient protectors will not work here because they act on large signals at a fixed level. In fact, with large signals, transient protectors can even make the situation worse through rectification and the creation of harmonics and cross-modulation products.

RFI filters must often work over a very broad frequency range, such as 10 kHz to 1 GHz, or more. To cover the entire range, most filters require two or three stages cascaded in series, because most components are only effective over a few frequency decades before parasitic effects take their toll. Parasitic effects cause "holes" in the attenuation. (See **box**, "Why filters fail.")

Ferrites are your friends for RFI just as they are for ESD. Generally, EMI ferrites are most effective in the frequency range of 50 to 500 MHz. Below 50 MHz, they have too little inductance and resistance. Above 500 MHz, lead capacitance becomes a limiting factor. Surface-mount ferrites work well into the GHz region because they have no exposed leads.

The loss factor of EMI ferrites is the key to their effectiveness, causing these ferrites to absorb copious amounts of energy above 50 MHz. As a rule of thumb, small ferrite beads look like 50 to 100Ω resistors at 100 MHz but have only a few ohms of inductive reactance at 1 MHz. This lossiness also helps damp oscillations or "ringing" that pure reactive elements might exhibit. The unwanted RF energy dissipates as heat, rather than simply diverting to another part of the circuit.

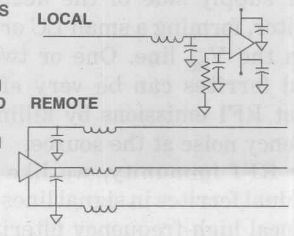
There are several cautions when using ferrites. First, be sure to use EMI ferrites, not low-loss ferrites. Second, be sure to couple the ferrites into a low-impedance load. A shunt capacitor of 100-1000 pF works quite well; keep the capacitor leads short to minimize unwanted lead inductance. Third, watch out for saturation caused by dc or low frequency currents. As a rule of thumb, small beads are good to about

Fig 5—Protecting analog circuits

DECOUPLE ALL VOLTAGE SUPPLIES TO ANALOG CHIP WITH HIGH-FREQUENCY CAPACITORS

USE HIGH-FREQUENCY FILTERS ON ALL LINES THAT LEAVE THE BOARD

USE HIGH-FREQUENCY FILTERS ON THE VOLTAGE REFERENCE IF IT'S NOT GROUNDED.



Why filters fail

Filters are an important defense against radio-frequency interference (both emissions and immunity), yet they often fail because of improper design or installation. Here are several potential problems with filters. Note: We'll assume they are all lowpass filters, the most common configuration used for controlling interference.

1. *Frequency range too wide:* Although ideal lowpass filters attenuate all frequencies above the design frequency, real filters start to "leak" at high frequencies because of parasitic capacitance and inductance (see **Fig A**).

As a rule of thumb, we expect filters to fail at about 100 to 1000× the design frequency. Thus, if you design a filter to cut off at 20 kHz, it will start to become ineffective above 2 MHz. By 20 MHz, that same filter may well be very ineffective.

The solution is to add multiple stages of filters, as shown in **Fig B.** The situation is analogous to the speakers in a stereo system, where you need separate speakers as woofers, midranges, and tweeters. We like to design the woofer filters for about 10 kHz to 1 MHz; the midrange filters for 1 MHz to100 MHz; and the tweeter filters for 100 MHz to 1 GHz.

2. *Filter location:* This is another source of potential problems. For a system using a shielded enclosure, a tweeter filter should be mounted as close to the shield as possible, preferably as a "feed-through" element in the shield. This minimizes high-frequency leakage at the cable penetration. For a system that is not shielded, the tweeter filter should be located close to the protected circuit to minimize unwanted pick-up or radiation from active circuit traces.

3. *Poor grounding:* Low-impedance connections are mandatory for good high-frequency filtering. **Fig C** shows this effect on a simple filter. The high impedance (could be resistance or inductance) actually lets the high-frequency energy bypass the filter.

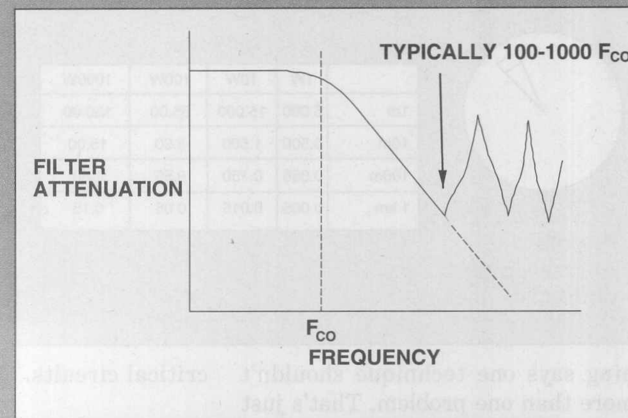


Fig A—Filter example.

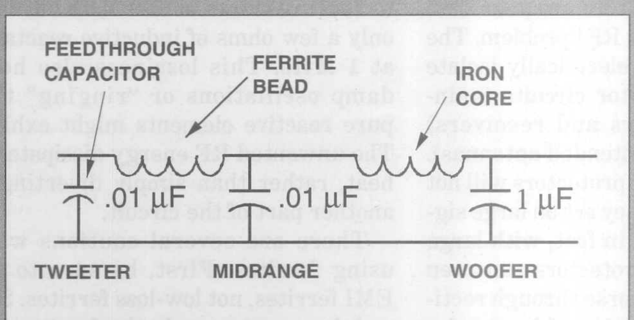


Fig B—Example of a 3-stage filter.

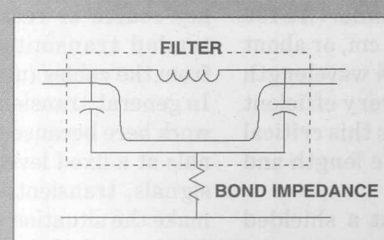


Fig C—Poor filter ground.

100 to 500 mA; beads the size of a 2W resistor are good to about 5 to 10A.

For RFI emissions, we like to use ferrites in clock lines and sometimes in microprocessor V_{CC} lines. In the latter case, the ferrite is installed on the power supply side of the decoupling capacitor, forming a small LC or RC filter on the V_{CC} line. One or two well-placed ferrites can be very effective against RFI emissions by killing high frequency noise at the source.

For RFI *immunity,* we like to use individual ferrites in signal lines to provide local high-frequency filtering. We also like to use clamp-on or bulk ferrites on signal cables and power wiring. These "common-mode" chokes can be very effective against common-mode currents induced on cables by high-level RF fields.

Multilayer boards are highly effective weapons in the war against RFI. We've seen emission reductions of 10 to 100 (20 to 40 dB) when changing from a 2- to a 4-layer board. Multilayer boards also increase RFI immunity.

These improvements are due to several effects, as shown in **Fig 8.** First, the "loop areas" of signal and power traces that can act as small transmitting or receiving antennas are reduced. At high frequencies, opposing currents induced in a nearby ground or power plane cause fields to cancel, spoiling these unwanted antenna effects. Second, the much lower ground impedance reduces high-frequency ground bounce. Third, the power-distribution impedance is lowered at high frequencies because of the distributed capacitance of the power and ground plane. This distributed capacitance also reduces high-frequency power-line ringing.

Incidentally, you don't always need multiple planes. A major miracle occurs with the addition of the first

plane. The real secret is to get the plane as close to the traces as possible to improve the cancellation effects. We've added ground planes to 2-layer boards with copper tape and have seen very significant improvements. We've also had success by adding a small local ground plane under individual microcontrollers on 2-layer boards. (We call this latter method "Micro Island," which we'll cover in more detail later.)

Protecting key circuits is a final piece of advice when dealing with RFI. More than 90% of the RFI problems are probably associated with fewer than 10% of the circuits. If we can identify and protect these critical circuits, we've gone a long way toward solving RFI problems. The most likely sources of RFI are oscillators, clocks, and other highly repetitive signals (address-latch enables or read/write controls). The most likely victims of RFI are low-level analog circuits or power regulators. We recommend adding additional high-frequency filtering of these circuits as well as hand routing the traces associated with these circuits.

The connector and cable area

The higher the frequency, the better the cable and connector must be. Cables act as unintended antennas (both transmitting and receiving) for radio-frequency energy. Connectors provide unintended leakage points to and from the cable shield. Even the best cable can be rendered ineffective by poor connectors. This is very important, as experience has shown that cable/connector problems are a major reason for failing commercial radiated emission tests.

Cables and connectors must be considered together as a system and not as individual components. A useful analogy here is to think of your cables as a garden hose. The connections to the faucet (and between the connectors and the hose) are just as important as the hose material itself. In fact, the best hose in the world will leak if the connections aren't tight. So it is with cables and connectors for RFI problems. Here are some recommendations:

1. Use high-quality shielding above 10 MHz. At frequencies below about 10 MHz, most cable shielding works pretty well. Above 10 MHz, leakage through the shield becomes a problem. In fact, the higher the frequency, the leakier the shield becomes. This is caused by a shield property known as transfer impedance.

You need to determine the highest frequency at which the shield must perform. If all your RF sources or problems are below 10 MHz (don't forget harmonics), then simple braid shielding should work well. At higher frequencies, we recommend high-coverage braids, or braid-over-foil shielding. Incidentally, solid foil works quite well at high frequencies, as long as it remains intact. If a foil shield is flexed, however, it may rupture and the shielding lost, which is why we prefer braid-over-foil to a simple metal-foil shield.

2. Use high-quality connectors. This is good advice at any frequency, but it is particularly important at frequencies above 10 MHz. The objective is to provide full 360° coverage all the way from the cable shield to the cabinet. Every joint must be watertight—shield-to-connector, connector-to-connector, and connector-to-chassis.

3. Don't use pigtails or drain wires to make a connection between the shield and connector or chassis. The impedance of such a connection is inductive and can be very high at even low radio frequencies. As a rule of thumb, we don't like to use pigtails above 10 kHz; they are fine if you are need protection against power frequencies (60-Hz hum in an amplifier, for example), but they completely ruin a cable shield at radio frequencies.

4. If you can't shield, then filter. For cables with data rates under 1 MHz, filtering may often be used in lieu of shielding. At 1 MHz, a wavelength is 300 meters, and most cables are not very efficient antennas at these frequencies and wavelengths. Even though the intended signals are at 1 MHz or below, you must provide filtering to prevent unintended higher frequency energy from sneaking into (or out of) the system via the cables.

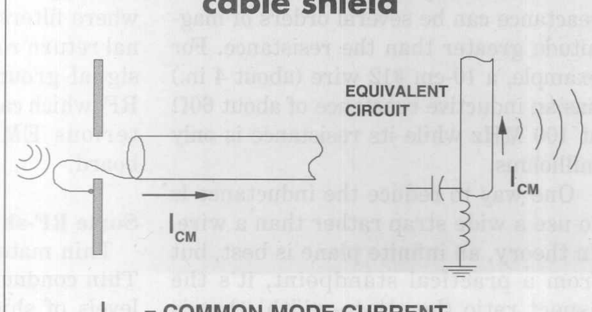
5. Small, high-frequency filters consisting of ferrites and bypass capacitors work well. Keep the leads short, and connect bypass capacitors to chassis ground, not circuit ground. Place the high-frequency filters as close to the connectors as possible to minimize noise pickup on wire traces. Better yet, use filtered connectors mounted right in the chassis.

6. Don't forget internal cables. Internal cables can also act as unwanted antennas, and they deserve your attention. Be careful with routing, and keep them away from enclosure seams and slots. We've seen numerous FCC emission failures caused by cables close to seams; the RF jumps from the internal cable to the "slot antenna" formed by seams or slots, which then radiates the

Fig 6—Cable lengths vs wavelength

Frequency	Wavelength	¼ wavelength	1/20 wavelength
10 kHz	30 km	7500m	1500m
100 kHz	3 km	750m	150m
1 MHz	300m	75m	15m
10 MHz	30m	7.5m	1.5m
100 MHz	3m	75 cm	15 cm
1 GHz	30 cm	7.5 cm	1.5 cm

Fig 7—Radiation from cable shield



unwanted energy. We've also seen several RF-immunity failures caused by internal cables running across seams, picking up RF from the "slot antenna." In either case the solution is simple: keep internal cables at least two inches away from seams and other openings. Common-mode ferrites that clamp over the entire cable can also be a big help in taming RF energy on internal cables.

7. If you are using ribbon cables, use the maximum number of ground returns and spread them throughout the cables. This minimizes "loop areas" that can also act as unwanted loop antennas. The best situation is a dedicated return line for each signal line, but our experience has shown that we often go as high as a 5:1 ratio of signal lines to return lines, as long as the returns are spread throughout the cable and not all grouped together at one end of the cable.

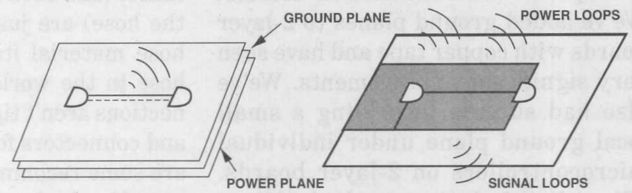
Some RF-grounding guidelines

Inductance is the killer in RF grounding. When dealing with grounding, most engineers get hung up on resistance and ignore inductance. This approach leads to all kinds of problems when dealing with radio-frequency energy. In fact, inductive effects predominate throughout the radio-frequency range, even at the low end of about 10 kHz.

As a common rule of thumb, a round wire has a self inductance of about 10 nH/cm. This rule of thumb is good for most wires we use in equipment design because the inductance is very insensitive to wire size. For most wire, the "inductive-reactance-per-unit length" exceeds the "resistance-per-unit length" above 10 kHz. By 100 MHz, the inductive reactance can be several orders of magnitude greater than the resistance. For example, a 10-cm #12 wire (about 4 in.) has an inductive reactance of about 60Ω at 100 MHz while its resistance is only milliohms.

One way to reduce the inductance is to use a wide strap rather than a wire. In theory, an infinite plane is best, but from a practical standpoint, it's the aspect ratio (length-to-width) that is important. For many years the military has recommended using a maximum ratio of 5:1 (length to width) for bond straps in radio and radar systems, but we have found cases where that is still not good enough. Therefore, we prefer a 3:1 ratio for RF and ESD grounds. Flat wire or braid alone won't work their miracles unless the aspect ratio is favorable. Keep those high-frequency grounds short, fat, and flat!

Fig 8—Multilayer vs 2-layer boards



MULTILAYER CIRCUIT BOARDS PROVIDE SEVERAL ADVANTAGES:

-REDUCED LOOP AREAS (SIGNAL AND POWER)
-REDUCED GROUND BOUNCE
-REDUCED POWER-DISTRIBUTION IMPEDANCE

Where you ground is as important as how you ground. When dealing with RF problems, we're usually using a "ground" to intercept or divert RF currents away from critical circuits or cables acting as unwanted antennas. Generally, the preferred place for an RF ground is as near as possible to the entry or exit point of a chassis. Putting grounding points close to entries and exits helps maintain the shielding integrity and minimizes common-mode cable currents by "shorting" them to the chassis.

For RF emissions, if you can only ground your board at one spot, make it as near as possible to the I/O connectors as you can. Better yet, ground your high-speed boards as often as you can through multiple short, fat, flat connections.

For RF immunity, shield grounding achieves an added benefit. The external RF currents are diverted away from both the vulnerable circuits and their signal grounds. The objective is similar to that for ESD protection. We often see RF immunity problems in systems where filters are connected to the signal return rather than the chassis. The signal ground is "modulated" by the RF, which can result in all kinds of mysterious EMI problems all over the board.

Some RF-shielding guidelines

Thin materials work fine as shields. *Thin conductive coatings provide high* levels of shielding over the radio-frequency range of 10 kHz to 10 GHz and beyond. Aluminum foil provides at least 90 dB over this frequency range. Thin metal coatings such as nickel or copper paints provide 40 to 60 dB of shielding, and vacuum plating and electroless deposition are good to 80 dB or more.

Thin shields are not effective for low-frequency magnetic fields, such as those from a power supply or magnetic deflection circuit. In those cases, thick steel or other ferrous materials are needed. Generally this is not an issue above about 20 kHz.

For now, just remember that thin, highly conductive materials will work very well to help solve most of your RF-emission and -immunity problems.

Slots and seams destroy RF shields. A major problem with RF shielding is leakage from slots and seams. These discontinuities act as "slot antennas" and actually radiate high-frequency energy, which is why you want to keep any internal cables away from slots and seams; they are hot with RF energy.

In addition, it's the longest dimension, not the area, that is critical. A long thin slot is like a long thin wire antenna—and both radiate equally well. A rule of thumb in the EMI world is to limit the longest dimension of any opening to 1/20 of a wavelength or less at the highest frequency of concern. For 100 MHz, this is about 6 in., and at 1 GHz, it's only about ½ in. Even this may not be enough, since the 1/20 rule provides only 20-dB attenuation through the slot.

Unfiltered penetrations also destroy RF shields. Any isolated conductor passing though a shield can carry high-

frequency energy right through the shield. All penetrations must either be bonded to the cabinet or decoupled with high-frequency filters. (Obviously you can't short out power and signal lines, so you filter them as they pass through the shield barrier.)

We can't emphasize this enough. We've seen high-performance shield rooms with over 120 dB of shielding turned into 20-dB "shielding wimps" because of single unterminated cable penetrating the shield. Fortunately, this problem is easy to fix if it's only one cable—you just add a bulkhead connector, and the shielding is restored.

Key points

Radio-frequency interference is a serious threat
- Equipment causes interference to nearby radio and television
- Equipment upset by nearby transmitters

RF-failure modes
- Digital circuits prime source of emissions
- Analog circuits more vulnerable to RF than digital circuits

Two strategic concepts
- Treat all cables as antennas
- Determine the most critical circuits

RF circuit protection
- Filters and multilayer boards
- Multistage filters often needed

RF shielding
- Slots and seams cause the most problems

RF cable protection
- High-quality shields and connectors needed for RF protection

Here's our advice for RF shielding: use a continuous metal coating with minimal seams. Filter or bond all penetrations to the shield. Keep the longest dimension of any opening under ½ in., if you need to go to 1 GHz, and keep all internal cables and critical circuits at least two inches away from seams and openings. You may need gasket material for seams and slots, so you should design your enclosures to add gaskets if necessary.

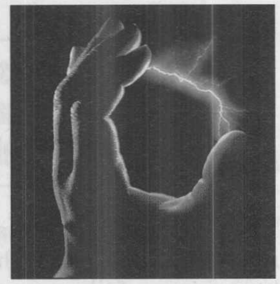
Some comments on RF testing

Presently, there are two types of RF testing: emissions, and susceptibility (or immunity). As we mentioned earlier in this chapter, most commercial electronic products are tested for emissions to determine if they will interfere with nearby television receivers. These tests are the FCC, VDE, or CISPR requirements.

For RF immunity, a key commercial standard is IEC 801.3, which prescribes electric-field levels of 1 to 10 V/m over a nominal frequency range of 27 to 500 MHz. This is the test procedure called out for new EC immunity requirements. Other organizations, such as the US Food and Drug Administration, are also using this procedure as a basis for their requirements.

We believe IEC 801.3 is a good test procedure with realistic levels and recommend it to clients even when a mandatory limit does not exist for their products or markets. Two exceptions are military contractors (they already have a set of well-defined tests, thanks to MIL-STD-461/462) and automotive suppliers (their tests are defined in SAE J1113). EDN

We hope you appreciate our rather broad look at this topic from two perspectives—emissions and immunity. You've seen that computers and communications electronics can antagonize each other. Neither side is blameless, but fortunately, careful design can resolve the problems. In the next chapter, we'll look at power disturbances, which we think will be a key EMI problem in the 1990s.



The Designer's Guide to Electromagnetic Compatibility

Chapter 5

Power disturbances as EMI problems

Power disturbances are often orphans of the EMI world. The equipment designer blames the power company, the power company blames the installer, and the installer blames the equipment designer. Meanwhile, it's often the user who is fouling his or her own nest by polluting the local power. One study showed that local pollution caused more then 85% of the power problems. Incidentally, as consultants, we are seeing an increase in power-disturbance problems, and we believe power disturbances will be a growing EMI problem in the 1990s.

Rather than point the finger, we all need to work together to prevent and to solve these power-related EMI problems. As design engineers, we need to build in more protection against power disturbances. We also need to understand better how to install equipment to minimize power problems in the field.

In this chapter, we'll examine how different power disturbances affect modern electronic equipment, and we'll discuss prudent design techniques that minimize these effects. We'll also look at two new power problems that are gaining attention—harmonics and magnetic fields.

Poor definitions hinder understanding

A major problem with power disturbances is a lack of common definitions within the engineering community. Terms such as spikes, sags, surges, and transients often have different meanings depending on their context. This situation is starting to change as different standards organizations get more involved with power disturbances. The newly released IEEE "Emerald Book" (IEEE STD 1100-1992 "IEEE Recommended Practice for Powering and Grounding Sensitive Electronic Equipment") has made a serious effort to standardize the terms. We'll use these new terms throughout the chapter.

A second problem is one of perspective, which was explained to us several years ago by Dan Nordell of *Northern States Power, a friend and* colleague who shares our concerns about power disturbances. Dan pointed out that power engineers are concerned primarily with 60-Hz issues, and up to about the tenth harmonic. (For many power engineers, 600 Hz and 600 MHz behave about the same.) On the other hand, to most electronics engineers, all mains power is low frequency and behaves the same way—50 Hz, 60 Hz, 400 Hz, or dc. Keep this difference in mind the next time you are chasing a power disturbance and be ready to adjust your perspective.

One study showed that over 85% of the power problems were due to local pollution.

Types of power disturbances

We divide disturbances into five groups: voltage variations, frequency variations, waveform distortions, transients, and continuous electrical noise. These groups appear in **Fig 1**. As you can see, there are many different power perturbations. So, let's look at these areas in a bit more detail.

Voltage variations: Recent convention names voltage variations using several classifications, based on duration. Voltage increases or decreases lasting from one-half cycle to a few seconds are now called *swells* and *sags*. Voltage increases or decreases lasting longer than a few seconds are now called *overvoltages* and *undervoltages*. Long-term losses of power (more than a few seconds) are called *interruptions* or *outages*. Voltage variations lasting less than one-half cycle are classed as *transients*.

Power utilities and users can cause power-line sags and undervoltages. Some examples of utility-caused sags and undervoltages are voltage drops resulting from clearing faults and "brownouts," which are deliberate reductions of voltage during peak-demand times. User-caused sags and undervoltages are caused by the turning on of heavy loads or high inrush currents on the same circuit. Deep sags and undervoltages can cause problems with electronic systems by leaving power supplies starving for energy.

Swells and overvoltages, on the other hand, are almost exclusively caused by utilities and result from sudden load changes or power-factor corrections. These disturbances rarely cause problems with electronic systems that incorporate regulated power supplies.

Interruptions or outages can last from a few seconds to several hours or more.

These disturbances usually result from severe weather, transformer failures, accidents, or tripping of circuit breakers. These events obviously cause problems, as anyone who has ever lost power to their personal computer can attest.

Frequency variations: These disturbances are changes in the sinusoidal power-line frequency usually caused by poor generator regulation. This disturbance is very uncommon in commercial North American power systems where the power-line frequency is typically held to 60 Hz ±0.5 Hz. In addition, any frequency deviations are averaged out over a 24-hour period to satisfy clocks and other time-based devices.

Frequency variations can be a concern for small, independent power systems, particularly as the load changes. Changes in line frequency can affect motors and ferroresonant transformers. Fortunately, small frequency changes do not affect most electronic systems' power supplies.

Waveform distortions: These disturbances include distortions of both current and voltage from a pure sine wave. Because any waveform other than a sine wave contains harmonics, waveform distortion is often referred to as harmonic distortion. A common term is total harmonic distortion (THD), which is simply the residual harmonic energy remaining after removing the fundamental frequency.

There are two types of harmonic distortion: voltage and current. Voltage distortion can be caused by faulty distribution equipment or high source impedance that converts any current distortion to voltage distortion. Current distortion is caused by nonlinear loads such as switch-mode power supplies that take narrow "gulps" of current at the peak of the power cycle (see **Fig 2**) rather than consuming current over the entire waveform.

Fig 1—Types of power disturbances

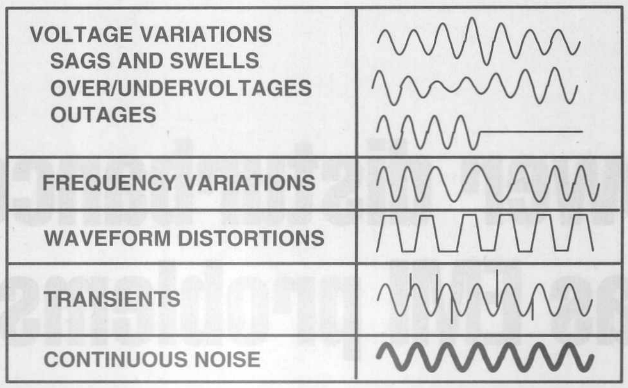
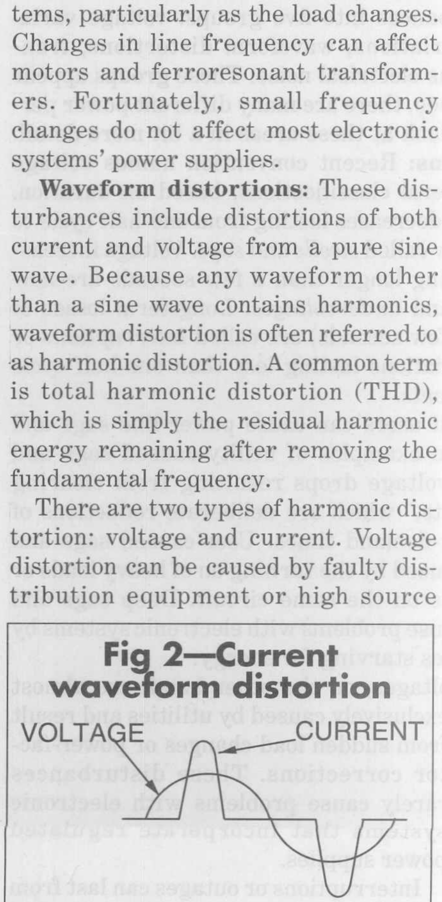


Fig 2—Current waveform distortion



Neither type of waveform distortion causes much of a problem with electronic equipment, but current distortion puts severe stresses on power-distribution equipment; it causes transformers to overheat, motors to malfunction, and even overheating of neutral wires in 3-phase systems.

On the receiving end

One might argue a certain poetic justice at work here. For years, electronic systems have had to swallow all kinds of power disturbances, and they are finally getting even by creating harmonics. But we, as equipment designers, must deal with the problems we are creating.

Europe already has regulations that limit harmonics generated by equipment. In the United States, the power utilities are applying economic pressure by charging higher rates to users that distort the power-line current. The net result of these political and economic pressures will be a demand for power-factor correction built into new electronic designs. We'll reexamine power-line harmonics later in this chapter.

Transients: These disturbances are short-term events (much less than one cycle or 16.6 msec at 60 Hz), which either increase (spike) or decrease (notch) the voltage waveform. Transients can last from nanoseconds to a few milliseconds, and amplitudes can range from a few volts to thousands of volts.

Transients pose a very serious threat to modern electronic systems. Their high voltages and energy levels can cause damage. Transients can also cause upsets due to fast rise/fall times. Digital systems are particularly prone to upset; a power-related "glitch" can be misinterpreted as a valid logic pulse and wreak all kinds of havoc. From an EMI-engineering perspective, we often refer to digital circuits as "glitch amplifiers" and call µPs "glitch multipliers" because they can reproduce a glitch millions of times per second.

Transients can originate inside and outside of a facility. Typical utility-related transient sources include lightning, power-factor capacitor switching, and power-distribution faults. Typical facility-related transient sources include motors, other inductive-load switching, and mechanical switch and relay contacts. The latter often result in the "showering arc," a series of high-speed pulses that can wreak havoc with µP systems.

Lightning and fast transients

Two common transient specifications that are applied to electronic equipment are the "lightning transient" and the "electrically fast transient," or EFT. These are voluntary specifications in the United States and are included in ANSI/IEEE C62.41. The same specifications appear in Europe as IEC 801.4 (EFT) and IEC 801.5 (lightning). The latter is still in draft form but is expected to be added to the suite of EC immunity test standards in the near future.

Continuous electrical noise: This category refers to disturbances that are repetitive at a much higher frequency than the line frequency. At lower frequencies, continuous electrical

noise includes hash from motor brushes, fluorescent lights, or devices such as switch-mode power supplies. At higher frequencies this noise includes radio-frequency interference (RFI) from nearby radio transmitters that is coupled onto the power lines.

Most modern electronic equipment can live with small levels of this continuous electrical noise, particularly if they already include EMI emission filters. Remember, EMI filters work in both directions and help keep unwanted noise out of a system as well as keeping system-generated noise contained. Nearby communications systems, however, can be adversely affected by continuous electrical noise that is radiated from the power lines. This type of noise often shows up as a raucous roar that can jam intended communications well into the VHF range.

Power disturbance failure modes

We've already touched on equipment failure modes, but let's look at these in more detail. Failures range from major damage to minor upset. Furthermore, different parts of the system can be affected by different types of disturbances. By understanding these effects, we can devise a design strategy to mitigate these problems. **Fig 3** shows some of these strategies.

Damage due to high levels: High-voltage transients are the most likely cause of damage. The most severe of these is the lightning transient (up to 6000V), which is often used as a "worst-case" test for all transients. If your equipment can pass the lightning-transient test, it won't likely be damaged by any other power-transient test.

The damage mechanisms associated with high-voltage transients are high-voltage breakdown and heating from excessive energy. The latter is why the lightning tests also have current requirements, because I^2R losses cause heating.

Acceptable damage

Incidentally, damage may be acceptable under these high-voltage/high-current conditions as long as the equipment is not left in an unsafe condition (or on fire!). This is typically the approach taken with consumer products such as televisions or VCRs, where the cost of full protection would be prohibitive. We don't recommend this approach, however, with industrial controls or other equipment where the "cost of failure" is high. In these cases, we prefer to protect fully against this threat.

Damage caused by slight swells or overvoltage is normally not a problem, particularly with systems using switch-mode power supplies or other forms of input voltage regulation.

Digital upset from fast spikes and noise: The most likely cause of power-related upset in digital electronics is high slew rates. Here, it's not the high levels but the high dV/dt or dI/dt that causes problems. The higher the slew rate, the more likely a spike will couple through parasitic capacitance or inductance and end up causing trouble in the form of false pulses.

As we move to faster and faster logic, this problem will only increase. Faster logic means higher frequency bandwidths, which means even more unexpected coupling of energy. As we are fond of saying, "The faster the logic, the wider the window of susceptibility." In the good old days, slower logic ignored much of this noise, but not any more.

When filters fail

Incidentally, we are often asked how these fast transients can get by all the filtering in the power supply. It's really quite simple. Most power-supply filters are designed to suppress ripple and become ineffective above 100 kHz to 1 MHz. Commercial EMI line filters may run out of attenuation above about 30 MHz, particularly if they are not carefully installed. Because much of the energy in high-speed transients exceeds 30 MHz, there is often nothing to stop them from entering a system.

High-speed transient effects have led to the relatively new electrically fast transient (EFT) tests prescribed by both IEC 801.4 and the newly released version of IEEE C62.41. These tests simulate real-world conditions and are a good test of how well you have protected against fast spikes.

Analog upsets due to sags and swells: Thanks to their low bandwidths, analog circuits are usually immune to fast power-line transients. However, analog circuits can be quite vulnerable to slow power-line variations such as sags and swells. These effects are particularly critical in low-level analog stages where small amounts of "power modulation" may be amplified by subsequent stages. This situation is really no different than amplitude modulation of a radio transmitter.

We've seen several problem cases of this sort in the past few years. The best defense against this problem is to provide local regulation for your critical analog circuits. In some application areas, such as medical devices, power-line sag and swell tests are being incorporated to test for this effect.

Memory loss caused by power sags or outages: If the mains voltage drops low enough for long enough, a system's power supply runs out of energy to power the electronics. If your system, has RAM, the data is lost unless you've taken special design precautions such as battery backup or power-loss detection.

We recommend having enough energy storage (ride-through) to continue unperturbed operation during a complete loss of voltage for at least 8.3 msec, or $^1/_2$ cycle at 60 Hz. More energy storage is better, of course, but many voltage losses are shorter than this duration. For example, a very common power loss is caused when transient-voltage

Fig 3—Power disturbance failure modes

Digital upset
- Due to spikes or EFT

Analog upset
- Due to sags/swells or under-voltages/overvoltages

Memory loss
- Due to energy starvation from under-voltages or outages

Damage
- Due to high voltage transients, such as lightning

Develop a power spec

You should develop an internal power specification for your designs. Here are some suggestions, based on several existing documents and test specifications.

Sags and swells, overvoltage and undervoltage: We recommend using the 'power-line voltage susceptibility' curve (**Fig A**) as a guide. This curve essentially says that your system should be able to withstand 106% overvoltage and 87% undervoltage power. It should be able to withstand a total loss of ½ cycle (8.33 msec at 60 Hz) of power. It should also be able to withstand a 300%, 100-µsec transient; a 200%, 1-msec transient, etc.

The curve in **Fig A** originally appeared in the National Bureau of Standards FIPS Publication 94 ("Guideline on Electrical Power for ADP Installations") and also appears in IEEE STD-446 (Orange Book, "Recommended Practice for Emergency and Standby Power for Industrial and Commercial Applications") and IEEE STD 1100-1992 (Emerald Book, "IEEE Recommended Practice for Power and Grounding Sensitive Electronic Equipment.") It is also widely referenced in power-disturbance literature. This curve has become a "de-facto" standard in the power industry, and we recommend using it as a design specification for equipment as well.

Transients (low level): We recommend using the "Electrically Fast Transient" (EFT) described in IEC 801.4 ("Electromagnetic compatibility for industrial-process measurement and control equipment—Part 4—Electrical fast transient/burst requirements.") This test is also included in the new version of IEEE C62.41 ("Recommended Practice on Surge Voltages In Low-Voltage AC Power Circuits"). This test simulates arcing on the power line caused by relays or inductive loads. These fast arcs can, and often do, cause upsets to µP systems, so we recommend that you include this test as part of a power-line design specification.

Transients (high level): For severe environments or very critical applications, we also recommend using the lightning- transient tests described in IEEE C62.41. These tests simulate lightning-induced surges on the power lines and as such, these tests involve large amounts of energy.

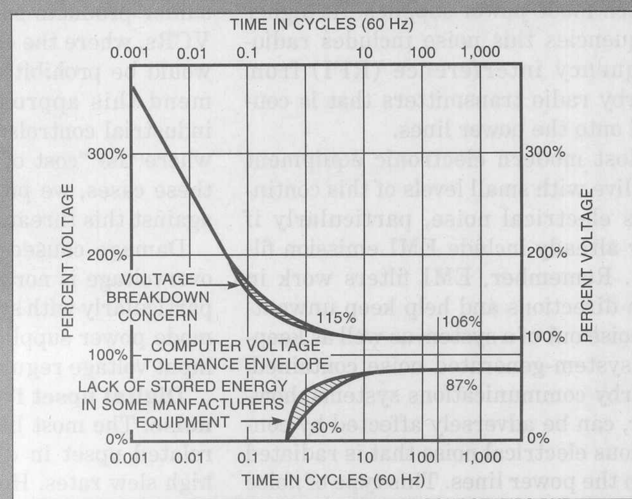


Fig A—Typical design goals of power-conscious computer manufacturers.

This test is often considered destructive. You are not normally expected to operate through this transient, but your systems must not be left in an unsafe condition after the transient. (Nor should it catch on fire!) If you include this test as part of your specification, have the testing done by experienced personnel; it can be dangerous if not properly done.

Continuous noise: We recommend using a subset of MIL-STD-461 Method CS02. The frequency range could be limited (for example 150 kHz to 80 MHz), and the amplitude should be 1 to 3V rms. Such a set of tests is similar to a draft standard for medical devices, which we feel is a realistic limit for RF energy coupled to the power lines.

suppressors "crowbar" at the beginning of a cycle but are commutated by the phase reversal of the voltage (**Fig 4**). Being able to ride through this type of disturbance makes your system immune to many momentary and self-correcting power losses.

Design for mitigation

Now that we've identified the problems and discussed their ramifications, let's look at how to prevent these power-related problems at the design stage. Or, as many in the power-disturbance business say, let's mitigate (rhymes with litigate) the problems. By adding suitable devices to your design, you may eliminate the need for external protection. You'll also end up with a more robust product and fewer mysterious field problems.

Before we begin, however, we need to cover a key concept. Power-line noise currents can flow in two modes, and both must be addressed; these modes appear in **Fig 5**.

Differential mode refers to disturbances in which the noise voltage appears between the individual current-carrying conductors. The current flows in the same direction as the intended current. For this reason, this mode is often referred to as normal mode.

Common mode refers to disturbances in which the voltage appears between both current-carrying conductors (line and neutral) and the ground wire. Common-mode currents flow in phase with each other on the line and neutral. This is often referred to as longitudinal mode. There are actually two types of common-mode noise. The first type uses the safety ground for a return; the second uses an external path for a return.

This distinction in noise modes is important for several reasons. First,

you will encounter both modes in the field, so if you address only one, you are only doing half the job. Second, some design approaches work only for one mode. For example, line-to-line capacitors are only effective against differential-mode disturbances and do nothing for common-mode disturbances. Third, the disturbance mode often gives a clue to the origin. Differential-mode disturbances are probably on the same mains circuit and are purely conducted. Common-mode disturbances are usually the result of crosstalk or radiation coupling.

One more point about the two modes: as a rule of thumb, differential-mode disturbances predominate at frequencies below 1 MHz, and common-mode disturbances predominate at frequencies above 1 MHz. Thus, smaller components may be used for common-mode disturbances, but more attention must be given to high-frequency installation methods.

Protection devices

Following are some common protective devices you can include in your equipment to minimize the effects of the more common power disturbances.

Transient protection: These devices divert power-line energy above preset voltage levels. Transient protectors include three types of devices: gas tubes, metal-oxide varistors (MOVs), and silicon Zener devices. Each type has pros and cons, resulting from different operating speeds and energy capabilities.

Transient protectors fall into two categories: clamps and crowbars. A clamp simply limits the voltage at a given threshold; the crowbar provides a momentary short circuit when the voltage threshold is exceeded.

Clamp protectors are large-geometry Zener diodes or MOVs. They operate by limiting the voltage to a fixed level and diverting the rest of the energy. Clamp devices must dissipate the energy internally, so they are typically rated in Joules of energy. Their response time is fast, with the Zeners being faster than the MOVs. Zeners are also a bit more rugged, as MOVs may eventually "wear out" due to their construction. MOVs, on the other hand, handle more energy for a given size. We prefer Zener devices for transients shorter than 10 nsec (such as ESD) and like MOVs for other power transients (such as EFT and lightning surge).

Crowbar protectors are usually gas-discharge devices. When the gas ionizes, the voltage across the ionized arc drops to a low level, and most of the energy is reflected rather than absorbed. The response time for crowbar devices is slower than clamp devices but still fast enough for lightning transients, for which they are very well suited.

Combined protection devices

Some commercial transient protectors combine both clamps and crowbars into a hybrid device. This sort of device offers high speed and high energy protection at a reasonable cost. You should consider these combination devices for rugged applications or as primary power protection. Inside equipment, the simpler MOV or Zener will usually suffice.

You should install transient protectors both line-to-line and line-to-ground to provide both common mode and differential mode protection. **Fig 6** gives an example of a hybrid device that provided both protection modes. A word of caution—the US permits line-to-ground protection, provided UL-listed devices are installed. Line-to-ground protection is not allowed in Europe unless the breakdown voltage exceeds 1500V, which does not provide much protection for your system.

EMI Filters: Unlike transient protectors, filters are linear devices that provide energy storage. Thus, they attenuate both spikes and notches in the power waveform. Because they are linear, they act proportionally instead of clamping voltages to a fixed level. Filters are well suited for removing low levels of continuous RF energy although they will attenuate high-speed (high-frequency) transients as well.

Most commercial power filters available today provide both common-mode and differential-mode protection. **Fig 7** shows a typical EMI filter, which combines both common-mode and differential-mode chokes with common-mode and differential-mode capacitors. Also shown is a small optional choke in the safety ground that helps with common-mode filtering. This optional choke can be quite effective against common-mode transients such as motor noise or lightning. The choke must be kept small

Fig 4—Loss of 1/2 cycle due to crowbar

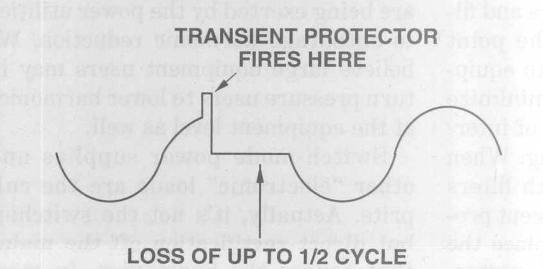


Fig 5—Common mode vs differential mode

- DIFFERENTIAL MODE (DM) - SIGNAL/RETURN FORM NOISE PATH
- COMMON MODE (CM) - NOISE POLARITY IS SAME FOR BOTH SIGNAL AND RETURN PATH, WITH CIRCUIT BEING COMPLETED BY A GROUND PATH
- DM PREDOMINATES AT FREQUENCIES <1 MHz
- CM PREDOMINATES AT FREQUENCIES >1 MHz
- NOTE TWO TYPES OF CM
  - FIRST TYPE USES SAFETY GROUND FOR RETURN
  - SECOND TYPE USES EXTERNAL GROUND PATH FOR RETURN

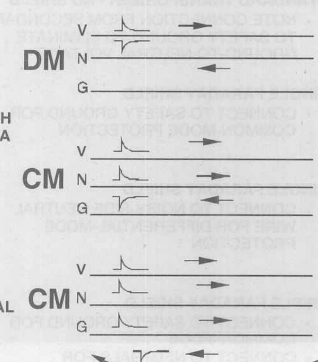


Fig 6—Hybrid transient protection

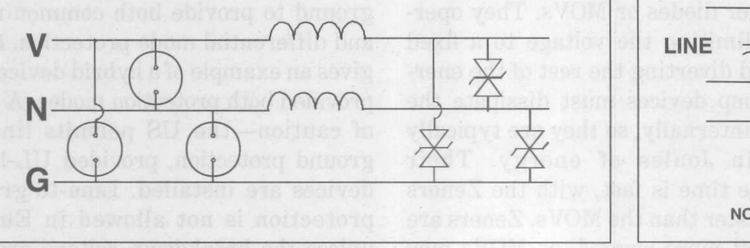
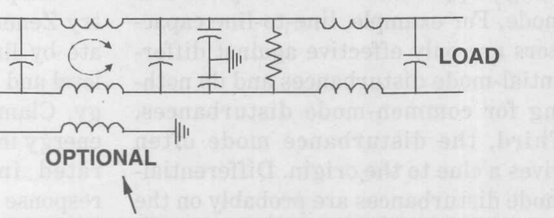


Fig 7—Typical EMI filter



NOTE: OPTIONAL CHOKE ADDED FOR COMMON-MODE PROTECTION

enough, however, so that it does not affect fault clearing at 60 Hz. The choke may cause other EMI problems, however, such as ESD.

Isolation transformers: These are power transformers with no dc connection between the primary and secondary. As a result, they provide "isolation" between input and output. Because transformers are differential devices, they also provide common-mode isolation.

How to shield transformers

Unfortunately, the isolation provided by a transformer degrades as the frequency increases, which is due to parasitic capacitance between the windings. The isolation can be improved at higher frequencies by adding capacitive (Faraday) shields between the windings to intercept unwanted currents. These shields can provide common-mode or differential-mode attenuation, depending on how they are connected.

The secret is to intercept the noise current and return the current to its source. For common-mode noise, the shield should be connected to the ground. For differential-mode noise, the shield should be connected to the neutral. If you need both modes, use two separate shields connected as shown in **Fig 8**. The shield connections must be kept short to minimize inductance.

Isolation transformers work best at low frequencies, under 1 MHz, or for transients with rise and fall times greater than about 30 μsec. Most motor noise and lightning transients are in this range, so isolation transformers work well for these types of disturbances. They do not work as well for high-speed transients such as the EFT (10 nsec) or ESD (1 to 3 nsec). Filters work well in these ranges.

Installation is important

Proper installation is important with any of the above devices. You must keep lead lengths short between ground and filters, transient protectors, and isolation transformers to minimize inductance. We recommend placing transient protectors and filters at the point of entry to equipment to minimize pollution of internal wiring. When using both filters and transient protectors, place the transient protectors next to the mains side to protect filters and other devices downstream.

You may need more than one of these mitigation methods, depending upon the problem you are trying to prevent or to solve. Remember that isolation transformers work best at low frequencies (under about 1 MHz), and filters work better at higher frequencies. Thus, the combination of filters and transformers can yield a range of protection. Similarly, transient protection is enhanced by using a fast Zener device in conjunction with a slower, but higher current, arc device. The key here is to use the right tool for the job.

Power-line harmonics

The Electronic equipment's generation of current harmonics is rapidly becoming a serious problem and should be a consideration in any new design. It now appears that by 1995, the EC will require compliance with the power-line harmonic limits of IEC 555-2. At this time the exact limits and power levels are uncertain, but there is little doubt that some limits will be applied to almost every piece of electronic equipment.

We don't expect to see mandatory limits in the US but economic pressures are being exerted by the power utilities to encourage harmonic reduction. We believe large equipment users may in turn pressure users to lower harmonics at the equipment level as well.

Switch-mode power supplies and other "electronic" loads are the culprits. Actually, it's not the switcher, but direct rectification off the mains that causes the harmonics. In most switchers, a full-wave rectifier charges a capacitor directly, with no interven-

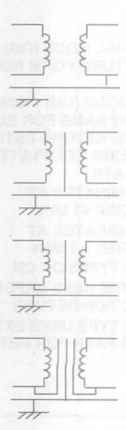
Fig 8—Isolation transformers

STANDARD TRANSFORMER - NO SHIELD
- NOTE CONNECTION FROM SECONDARY TO SAFETY GROUND TO ELIMINATE GROUND-TO-NEUTRAL VOLTAGE

SINGLE FARADAY SHIELD
- CONNECT TO SAFETY GROUND FOR COMMON-MODE PROTECTION

SINGLE FARADAY SHIELD
- CONNECT TO NOISY-SIDE NEUTRAL WIRE FOR DIFFERENTIAL-MODE PROTECTION

TRIPLE FARADAY SHIELD
- CONNECT TO SAFETY GROUND FOR COMMON MODE
- CONNECT TO NEUTRALS FOR DIFFERENTIAL MODE



ing components. This "bulk dc" is then converted to the desired output voltage or voltages through a dc/dc converter. The current for charging the capacitor is taken only at the peak, not over the entire sine wave, so severe current distortion results.

So what, you say? My piece of equipment only accounts for a tiny fraction of the power consumed in a building, so these effects are negligible, right? Unfortunately, the effects are not negligible because every "electronic" load is trying to gulp current at the same time, and electronic loads are increasing at an astronomical rate. In addition to switch-mode power supplies, electronic loads include variable-speed motor drives and electronic ballasts. In some modern buildings, well over half the load is "electronic," and that share is increasing.

Harmonic consequences

The effects of harmonic distortion on the power-distribution system are very serious. High harmonic currents cause overheating in transformers and motors, and can even burn up neutral wires in 3-phase systems. The latter results because triple harmonics (odd multiples of 3, such as the 3, 9, 15...) add, rather than cancel, in a 3-phase system. For this reason, the National Electrical Code no longer allows derating of neutrals for circuits serving electronic loads, and Underwriters Laboratories recognizes "K-rated" transformers which are increasingly popular for nonlinear loads. As equipment designers, we will be expected to do our part to reduce the current harmonics we generate.

Fortunately, devices are available to reduce harmonics generated from power supplies. They all work on the principle of spreading the current gulps over the entire cycle, which greatly reduces harmonic distortion. The costs of these devices are quite reasonable, even for very cost-sensitive products. We expect them to become universal in the next 10 years.

Magnetic fields: A quirky power problem

Magnetic fields are another power disturbance to be aware of. Concern is growing over the biological effects of power-line magnetic fields; and, these concerns are not limited to overhead power lines. Consequently, any system that uses electrical power may come under scrutiny. Frankly, we're not convinced there is a real problem (neither does the IEEE Committee on Man and Radiation), but often it's the perception of a problem that must be dealt with. In any event, we may find ourselves facing magnetic-field emission limits in the next few years. The IEEE is already working on them.

A real problem that often occurs is magnetic-field interference with video displays (CRTs). The source can be power lines, power supplies, or deflection circuits. We've seen several cases of "wiggly" CRTs caused by another monitor nearby. We've also seen cases of UPS systems interfering with CRTs due to magnetic fields from the power transformer.

If you're facing this problem, the first step is easy: move the equipment. Fortunately, magnetic-field intensities decrease at a very rapid rate (as the cube of the distance for transformers, and as the square of distance for power lines), so often even a few feet of separation is enough. If the noise source is power wiring, twisting the wires (if possible) can be very effective, assuming the wires are carrying equal and opposite currents. Installing the power lines in rigid conduit (not thin wall) can also help. If these solutions don't work, then you need magnetic-field shielding, which can be both difficult to add and expensive. For individ-

Key points

Several types of power disturbances
- Voltage variations—sag/swell, under/overvoltage, out
- Frequency variations
- Waveform Distortions (harmonic distortion) both volt age and current
- Transients (spikes and notches)
- Continuous electrical noise

Power-disturbance failure modes
- Damage due to high transient levels
- Digital upsets due to fast spikes and continuous noise
- Analog upsets due to sags and swells
- Computer memory loss due to energy starvation

Common mode vs differential mode
- Differential mode predominates below 1 MHz
- Common mode often due to crosstalk, radiation, or parasitics
- Both modes must be addressed

Protection devices
- *Transient protectors—crowbars and clamps*
  - Arc devices—Heavy current, but slow
  - Metal-oxide varistors—Moderate speed and moderate currents
  - Silicon devices—Fastest, but lowest current
- EMI filters—provide energy storage for transients
- Isolation transformers
  - Work best for frequencies under 1 MHz
  - Separate shields needed for both common mode and differential mode

Power-line harmonics
- Caused by "nonlinear" loads like switch-mode power supplies
- Result in stress and damage to transformers, motors, and wiring
- European regulations emerging (IEC 555-2)

Magnetic fields
- Perceptions of possible health issue may force regulations

ual CRT problems, external magnetic-field shields are available that work quite well.

Some comments on power testing

As we've mentioned earlier, this series focuses on design, not test. Nevertheless, here are some quick comments on testing for power disturbances:

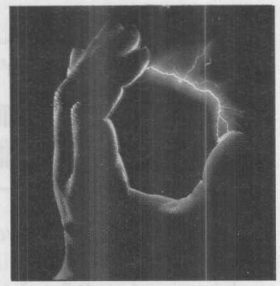
Presently, four key test standards exist for equipment. The first two are IEC 801.4, the test for the electrically fast transient (EFT), and IEC 555-2, the test standard for power-line harmonics. Both tests have been incorporated into the EC standard, so if you are designing equipment for sale in Europe, you need to meet these standards. A third standard is ANSI/IEEE C62.41, which addresses both the lightning transient and the EFT. This is voluntary, but you may want to meet it anyway.

Incidentally, IEC 801.5, which is now in draft form, is expected to adopt the lightning-transient specifications of IEEE C62.41 in the near future, so that spec may also become mandatory in Europe. A fourth standard is MIL-STD-461. Although this specification applies to military equipment, many organizations use parts of MIL-STD-461 for power-line testing. Two common tests are method CS06, a power-line spike, and CS02, which injects an RF level on the power lines.

Two related documents that set test limits are IEEE Power Engineering Society "Orange Book" on emergency power systems (ANSI/IEEE 446), and the newly released "Emerald Book" (IEEE STD 1100-1992) on power and grounding for sensitive equipment (See **box**, "Develop a power spec").

Regardless of your compliance requirements, we recommend that you develop both a power-disturbance design standard and a test standard for your products. Power-disturbance problems are not going to go away; the prudent equipment designer will not ignore them.

That's it for this chapter. We hope you learned something about power disturbances as an EMI problem. You've seen how power-line EMI affects your equipment, as well as how your equipment affects the rest of the world. You've also learned some techniques to prevent and solve these problems. In the next chapter, we'll look at how to design for EMI at the printed-circuit-board level.



The Designer's Guide to Electromagnetic Compatibility

Chapter 6

Circuit boards... bulletproof yours against EMI

All EMI (electromagnetic interference) problems begin and end at the circuit level. Some of you might argue with this thesis, of course. Lightning and ESD cause EMI problems, but are they circuits? They are not intended circuits, but they certainly can be considered as unintended circuits. In fact, many EMI problems are the result of unintended circuits that create sneak paths to unsuspecting receptors of energy. When dealing with EMI, what you don't know can hurt you.

You can take two approaches toward fighting EMI at the circuit-board level. You can practice source suppression, circuit hardening, or both approaches. Your specific EMI requirements, balanced against the normal constraints of cost, complexity, and time to market, will dictate the approach you take.

In this chapter, we'll look at circuit-board designs that prevent common EMI problems. We'll give you a set of guidelines that we've dubbed our "10 Commandments of Board Design." There may be other commandments, and you may have a favorite commandment not shown here. But if you follow these guidelines, we believe over 90% of your circuit-board-related EMI problems will be under control.

Define your objectives before you begin

As the old saying goes, "If I don't know where I'm going, any road will take me there." Before we start on our little journey into pc-board land, we need to know where we are going and why we're going there. What are the objectives, and what are the constraints? Here are five questions we ask our clients when we begin working with them on EMI circuit-design issues.

(1) What are you designing? Is is a supercomputer or a control system? What type of technology does the design employ (analog, high-speed digital, motors and relays, etc)? Who will use it? At this point, you don't need detailed information—just the big picture.

(2) What are your EMI requirements? Are there EMI-specific regulations to meet (FCC, VDE, CISPR, MIL-STD-461)? If so, do you know how your equipment category (Class A or B for commercial regulations, environment for military regulations)? Are there voluntary requirements that might apply (industrial standards, company guidelines)? Are you specifically exempt from certain regulations? At this point, you need to determine what requirements you must meet.

(3) What is your intended environment? Is it electromagnetically harsh? Is the power line noisy? Are there lots of radio transmitters in use? What do you anticipate over the next five or 10 years?

Even if you are exempt from mandatory EMI requirements, you may want to apply your own internal voluntary standards. For example, industrial controls are generally exempt from both emission and immunity standards in the United States, but many industrial manufacturers apply their own stringent EMI standards to their products. At this point, you need to determine what standards and specifications you should meet.

(4) What are your nontechnical constraints? What are your typical product costs? What are your anticipated volumes? What is your market window? Although nontechnical, these are valid engineering concerns. If you have a high-volume, price-sensitive product, then shaving the last few pennies out of your EMI "fixes" makes sense. On the other hand, if you are building only 100 units and each one costs $100,000, it's probably cheaper to overdesign than to optimize the design. Look at the total life-cycle costs—not just the individual component cost.

(5) What is the cost of failure? What happens if your equipment fails in the field? (A single field failure can easily cost thousands of dollars.) How much will it cost for you to to retest and requalify your equipment? (Typical costs range from $25,000 to $50,000 when you factor in engineering time.) How much will it cost if your equipment ends up in court? (Probably $100,000 and up. We've seen several cases where EMI was blamed in a lawsuit—right or wrong, it happens.) Our advice is to look at your downside risk and consid-

All EMI problems begin and end at the circuit level.

er that as you make your EMI decisions.

After you've defined your objectives, you're ready to begin. By the way, don't be afraid to make tradeoffs. In our opinion, that's an important part of the engineering game. And when you do make tradeoffs, always have a backup plan in case your first plan doesn't work.

10 commandments of design

These are the steps we go through when evaluating a circuit board for EMI problems. They work both in the design (prevention) stage and in the troubleshooting (problem) stage. Our emphasis here is on digital circuits and their effects on both emissions and susceptibility, but we'll address some special analog concerns too.

I. Identify critical circuits

Our experience suggests that more than 90% of the EMI problems are caused by fewer than 10% of the circuits. The good news is that by identifying and addressing these critical circuits, many EMI problems can be prevented or solved with very little effort.

For emissions, the biggest problems are highly repetitive signals such as clocks and buses. These signals are rich in high-frequency harmonics and are a ready source of high-frequency emissions. The most likely EMI sources are clocks, followed by buses and highly repetitive control signals such as address strobes. Even bit 0 of an address bus can cause occasional problems.

Two key parameters are clock rate and rise/fall times. Fast clock rates and short rise/fall times translate to high-amplitude harmonics at high frequencies. If this high-frequency energy is coupled to a cable or other unintended antenna, radiated emissions result. It takes very little energy to cause problems, and even a few microamps can cause FCC or VDE failure.

For susceptibility problems, the biggest culprits are reset lines, interrupts, and control lines. The entire system can be brought to a halt if these circuits are upset. Fortunately, it is relatively easy to protect these critical circuits.

A key parameter here is bandwidth. Most digital circuits today can respond to glitches in the 1- to 3-nsec range (representing a bandwidth of 100 to 300 MHz). This is much more response than is needed by most reset or interrupt circuits. Since these circuits do not need to operate at such high speeds, simple decoupling or filtering can prevent or solve many problems. For example, we've solved several vexing ESD problems by simply adding a small RC network at the reset line to decrease its response to noise.

Input/output (I/O) circuits are critical for both emissions and immunity because they are connected to the outside world. I/O cables act as antennas for radiated energy or conduits for conducted energy.

A key parameter here is location. A common problem we see are I/O circuits, or traces, placed close to clock or oscillator lines, which then couple unwanted high-frequency energy into the I/O cables. Another common problem is vulnerable signal traces (reset, interrupt, control) routed close to an I/O line and picking up transients from the outside world. **Fig 1** gives examples of coupling from critical circuits. It makes sense to identify the root causes of our EMI problems and to do everything we can to address them at the circuit level.

II. Choose devices with EMI in mind

We realize that not everyone has the luxury of choosing the components they use. Many companies have preferred parts, and there may be other good reasons for choosing a device or logic family. Nevertheless, devices do affect EMI. Even if you can't choose your devices, you need to be aware of the EMI issues.

You've already seen that emissions are driven by both clock speeds and rise times, and immunity is driven primarily by rise times (bandwidth). Thus, older, slower logic generally creates fewer EMI problems.

You need to be careful in upgrading a design with faster "pin-compatible" logic. For example, we've seen several cases where the old design was solid, and the new design with faster chips failed. Remember, with immunity issues, only the edge rate is the issue, not the clock rate. Watch out for "upgrades" too. Many years ago, one of us was involved with an embarrassing product recall when newer, faster memory chips in an upgraded board started failing during the winter due to ESD. The older, slower memory

Fig 1—Coupling from critical circuits

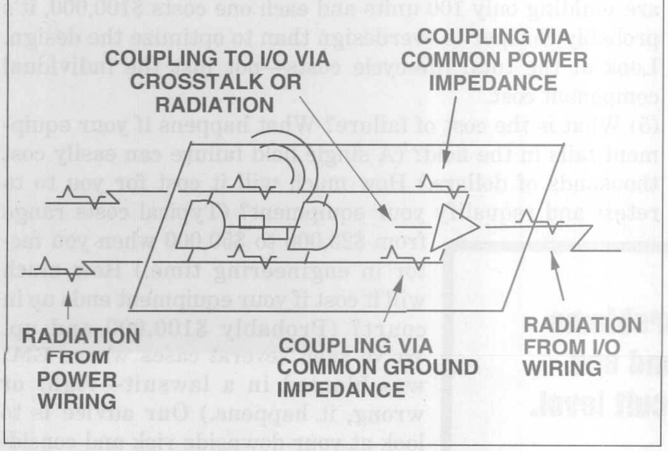


Fig 2—EMI characteristics of high-speed CMOS

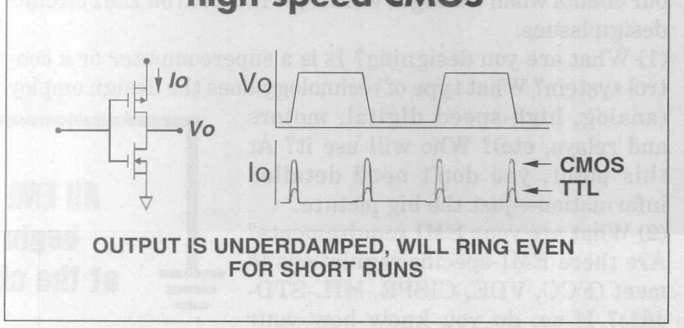
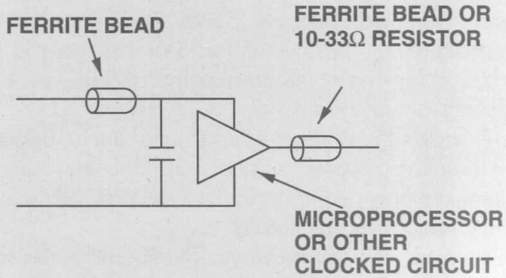


Fig 3—CMOS circuit treatment



chips in the same board worked just fine.

Slowing the clock rate can help with emissions, even without changing the logic. For example, increasing a 5-MHz clock to 15 MHz increases the emissions at any given frequency by a factor of three, or about 10 dB. (At 45 MHz, you have the ninth harmonic of a 5-MHz clock, while you have only the third harmonic of 15 MHz. The lower the harmonic number, the higher the emission level.) Slowing the clock can be a cheap and dirty way to reduce your emissions; it really works.

Watch out for high-speed CMOS logic. The conventional wisdom is that CMOS devices are electromagnetically quiet due to their low power consumption. Unfortunately, this is not true with high-speed CMOS devices. High-speed CMOS logic consumes current in narrow spikes (see **Fig 2**), which can cause serious harmonic-emission problems on V_{CC} lines. This is also why CMOS power consumption increases with speed.

We've seen several cases where changing from an NMOS device to a CMOS device resulted in a substantial increase in radiated EMI emissions due to the higher peak currents. The solution is to improve the decoupling between V_{CC} and ground on all CMOS circuits that are being switched or clocked. Do this as close as possible to the circuit, and keep the bypass capacitors' leads short. Adding a small ferrite bead in series with the V_{CC} line, as shown in **Fig 3**, can also help reduce emissions by isolating the transient CMOS currents from the rest of the system.

Another high-speed CMOS problem can occur on the signal lines. CMOS signal outputs are underdamped and ring even with very short traces. This ringing can show up as an emission that appears resonant, much like a tuning fork. The solution here is to add a small damping resistor (typically 10 to 47Ω) or a small ferrite bead in series with CMOS outputs that carry clocks or other highly repetitive signals. This is also shown in **Fig 3.**

III. Choose a board design

If everyone used multilayer circuit boards with ground planes, there would be a lot less EMI. Our experience shows that moving from a 2-layer pc-board design to a multilayer design can easily make a tenfold improvement. Emissions are reduced, and immunity against both RF and ESD is improved at the same time.

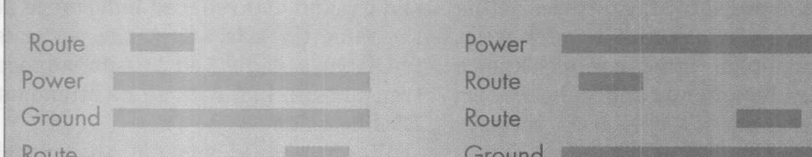
Unfortunately, not everyone can afford to use multilayer pc boards. In those cases, you can simulate a multilayer board by routing critical lines (clocks, resets, etc) with adjacent ground returns. You can also route power traces as power/return transmission lines, making those "antennas" less effective as well. Filling in unused areas with "ground" also helps. With very careful layout, you can achieve a quiet and stable 2-layer design. It's not easy, but it can be done.

EMI test failures can negate the economy of 2-layer boards. An extra round of testing can easily cost you $25,000 or more for redesign and retest, plus six to eight weeks of schedule. Depending on your volumes, a multilayer board may actually save you money. We've seen too many cases where $50,000 was spent in engineering costs to save $10,000 in production costs. Consider the total cost, not just the per-unit cost.

Over the years, we've come up with our "five-five" rule for multilayer boards. If your clock frequency is greater than 5 MHz or if your edge rates are less than 5 nsec, you are a good candidate for multilayer boards. We've pushed 2-layer technology to 15 MHz, but it gets very difficult above about 10 MHz, and there is little margin for error. It's like going from 50 to 150 mph—you can do it, but at 150 mph, even a small mistake can be fatal. And above 150 mph, you'd better be driving a high-performance race car.

The ground-plane miracle occurs because of the "image-plane" effect. Place a current-carrying wire close to a metal surface, and most of the high-frequency current returns directly

Fig 4—Embed the traces?



Pros

- Lower impedances, therefore, lower emissions and crosstalk
- Reduction in emissions and crosstalk is significant above 50 MHz
- Traces are protected

Cons

- Lower interboard capacitance, harder to decouple
- Impedances may be too low for matching
- Hard to prototype buried traces

The EFFT, or Extremely Fast Fourier Transform

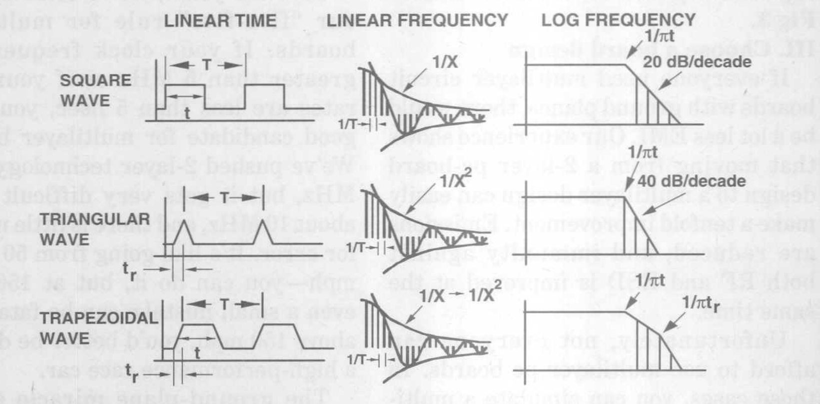
First there was the Fourier Transform—then the Fast Fourier Transform (FFT)—and now we have what we call the Extremely Fast Fourier Transform (the EFFT). Not only is it extremely fast, it's extremely useful when dealing with EMI problems, since it lets us move with ease between the time and frequency domains. It helps explain why clock rates and risetimes are so crucial for EMI control in digital systems.

Most of us live in a linear, time-domain world. We're used to viewing waveforms, digital or analog, as linear levels plotted against linear time. Many EMI issues, however, are easier to understand when viewed in the frequency domain, particularly when we also use logarithmic scales. Don't panic—we're just talking about our old friends, Bode plots, with their simple straight-line approximations. We can gain a lot of insight by just looking at the breakpoints and slopes of some common digital waveforms.

Fig A shows three views—linear time, linear frequency, and log frequency. It's very easy to move between these two, since there are only two important parameters—pulse-repetition time (T) and rise/fall time (t_r).

Let's start with the square wave. The Fourier series tells us that a square wave is composed of a series of harmonically related sine waves. For a perfect square wave with a 50% duty cycle, the even harmonics cancel and the odd harmonics decrease as the inverse of the harmonic number. That is, the third harmonic amplitude is one-third the fundamental, the fifth harmonic is one-fifth the amplitude, etc. If we plot this on a linear frequency scale, we end up with a bunch of spectral lines that are bounded by the (sin x)/x function. (Were you confused, as we were, the first time you saw this in school?) We make it simpler in the EMI world, however, since we care only about the worst case. Set the sin x=1, and we now have a simple 1/x curve. Better yet, plot this as a Bode plot (log frequency vs dB amplitude), and you get a straight line with a 20-dB

Fig A—The Extremely Fast Fourier Transform (EFFT)



under the wire. A transmission line is formed by the "mirror image" of that wire, or trace, over the metal surface. With equal and opposite currents, these transmission lines do not radiate very well (as opposed to single traces acting as antennas, which radiate very well). The image-plane effect has been known for years by antenna and radio-system designers, but it's only been recently discovered by digital designers. Nevertheless, it works very well for high-speed digital circuit boards.

The miracle occurs with the introduction of the first ground plane. You don't need multiple planes to benefit from the image-plane effect. We've demonstrated tenfold improvements by simply adding a single plane of copper tape to an existing 2-layer board.

Having separate power and ground planes, however, can offer further improvements. You can minimize power-generated EMI by feeding the power from two adjacent planes. The parallel planes offer two advantages: increased capacitance between power and ground and reduced inductance at the same time. In effect, the power is fed from a dedicated low-impedance transmission line with all its attendant EMI benefits.

Where should you put the signal traces? We are often asked whether it is better to place traces inside or outside the power and ground planes. On 4-layer boards, we prefer to put the traces on the outside. The image-plane effect is already working for us, and we prefer to keep the power and ground planes as close as possible to each other. Besides, component radiation is often greater than trace radiation on a multilayer board, so you achieve little, if any, reduction by burying the traces.

Beyond four layers, we like to keep all signal traces within one layer of a ground or power plane. In this case, you might as well place critical traces (clocks, resets, etc) on inner layers. There is no penalty, and you may pick up some additional shielding benefits. See **Fig 4** for the pros and cons.

We are also asked about segmenting the ground and power planes on multilayer boards. Properly executed, this technique can be quite effective. If you are not careful, however, you can undo the isolation and end up worse than you started.

It is very important with divided planes to eliminate any overlap in planes or traces, as shown in **Fig 5.** You can apply what we call the "chain-saw law"—if you cut through the isolation barrier, you cut through only those

decade slope that has a breakpoint at $1/\pi t$. You can't get much simpler than that, can you?

We can go through the same hocus pocus for the triangular wave, and we end up with harmonics that decrease as $1/x^2$. This gives a Bode plot with a 40-dB/decade slope, and a breakpoint of $1/\pi(t_r)$. Obviously, the harmonics from a triangular wave decrease much faster than from a square wave.

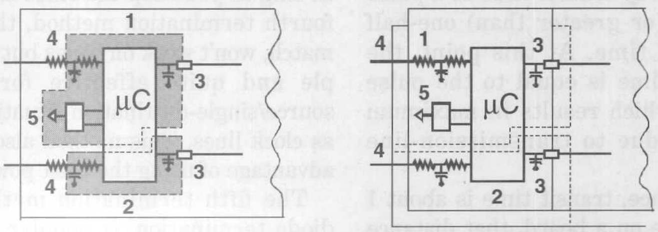
Which brings us to the trapezoidal wave. In the real world, all digital waveforms are trapezoidal, since we always have finite rise/fall times. The trapezoidal wave acts like a square wave at low frequency but then acts like a triangular wave at high frequency. The Bode plot for a trapezoidal wave has two breakpoints—the first at $1/\pi t$, and the second at $1/\pi(t_r)$, where the slope changes from 20 to 40 dB/decade.

In the EMI world, we use this last frequency, $1/\pi(t_r)$ as a critical design frequency. This does several things for us:

- It establishes a reasonable upper frequency limit for emissions due to harmonics. (This frequency defines the point where harmonics start to decrease at a rapid rate, 40 dB/decade).
- It establishes a reasonable EMI bandwidth for immunity. (This frequency defines an upper frequency to which a digital or analog circuit responds. This is the same approach used by oscilloscopes—you need a 100-MHz scope to see 3-nsec rise times, a 300-MHz scope for 1-nsec rise times, etc)
- It demonstrates that rise time control is a very effective tool in EMI control for both emissions and increased immunity at the same time. (We believe in EMI bandwidth conservation—don't waste it if you don't need it. To paraphrase Will Rogers, "They ain't making it anymore.").
- One last piece of information. The EFFT also works on single events, such as transients. That is why we say ESD is a 300-MHz phenomenon (1 nsec=316 MHz), and lightning is a 300-kHz phenomenon (1 μsec=316 kHz). Now you can move between the time and frequency domain extremely quickly.

Fig B—Micro-island

2-LAYER VERSION | MULTILAYER VERSION



2-LAYER VERSION:
1 DEDICATED DIGITAL POWER/GROUND PLANES
2 DEDICATED ANALOG POWER/GROUND PLANES
3 DIGITAL AND ANALOG POWER DECOUPLING
4 I/O DECOUPLED WITH FERRITE/RESISTOR AND CAPACITOR
5 GROUNDED CRYSTAL OR RESONATOR

MULTILAYER VERSION:
1 GROUND PLANE UNDER MICROCONTROLLER
2 SEPARATE ANALOG GROUND PLANE
3 POWER DECOUPLED WITH FERRITE AND CAPACITOR
4 I/O DECOUPLED WITH FERRITE/RESISTOR AND CAPACITOR
5 CRYSTAL OR RESONATOR OVER DIGITAL GROUND PLANE

traces sourced from or destined to the isolated plane. All other traces must not cross the barrier, and the planes must not overlap.

If additional high-frequency isolation is needed, you can isolate one plane (V_{CC}) or both planes (V_{CC} and ground) with ferrites. Be careful with this technique. If both plane areas contain high-frequency circuits, it's usually better to isolate only the V_{CC} plane and then to run all the interconnecting signal lines over a narrow ground "bridge." This approach maintains the image plane necessary for high-frequency EMI control.

If one plane area contains only low-frequency circuits (such as low-speed analog) and the other area has high-frequency circuits, you may find some improvement in isolating both planes (V_{CC} and ground) with ferrites. This technique works only if no high-speed circuits pass between the two areas. If both areas contain only low-frequency circuits and there are no other high-frequency threats, then no ferrites are needed, and you can use single-point connections to connect the different V_{CC} and ground planes.

IV. Do the initial layout

Now that you've selected the components and the board, you're ready to place your components and route the traces. You may be tempted to hand everything over to the pc-board design group at this point, but if you are concerned about EMI, you must stay involved. We've seen several cases in large companies where the difference between quiet and noisy designs was due to working with the board designers and not just walking away. (If you are doing your own layout, you don't have this problem. You already own all of the problems, right?)

Separate high- and low-speed circuits. This piece of advice is obvious but often overlooked. **Fig 6** gives an example. Watch out for routing from one section to another—we've seen problems caused when low-speed traces run through a high-speed area and become corrupted by crosstalk. Pay particular attention to oscillators and crystals, and keep them at least 1 in. away from external I/O circuits, internal cables, and connectors. (Keep the I/O circuits close to their connectors, too.)

Hand-route critical lines. If you've followed our first commandment (identify critical circuits), you already know which traces are most likely to cause EMI problems. We suggest hand-routing these lines or at least checking them very carefully if you insist on autorouting them. As we are fond of saying,

"Autorouters will route your traces to maximize EMI."

Many fine articles have been written on terminating traces, so we'll just quickly review this subject. A generally accepted criterion for termination is when the 1-way transit time of a pulse is equal to (or greater than) one-half the rise/fall time. At this point, the round-trip time is equal to the pulse rise time, which results in maximum reflections due to transmission-line effects.

In free space, transit time is about 1 ft/nsec, while on a board, that distance drops to about 8 in. (20 cm). Based on this criterion, you get about 4 in. of trace length for each nanosecond of rise time before terminations are needed. We've experienced problems with this criterion however, so our rule of thumb is to reduce this by a factor of two. This means that you should terminate board traces longer than 2 in. (5 cm)/nsec of rise time. **Fig 7** gives examples for several logic families and rise times.

Fig 8 shows several popular termination methods. The first three (resistive, RC, and Thevenin) all work well on buses, as long as you keep the stubs short. The fourth termination method, the series match, won't work on buses but it is simple and quite effective for single-source/single-destination situations such as clock lines. This method also has the advantage of using the least power.

The fifth termination method, the diode termination, is popular for ECL and GaAs devices but should not be used for signals going off the board. While it may keep the signal clean, it does not limit high-frequency harmonics.

V. Pay attention to power decoupling

We continue to be amazed that so many EMI emission problems are caused by poor power decoupling. While everyone intuitively understands that clock signals can cause EMI problems, many forget about power perturbations. It's like locking up your front door but leaving the back door wide open.

Every digital circuit that is switching is "gulping" current at its switching rate. These pulses of power current can and do radiate just like pulses of signal current. We saw earlier in this chapter that low-power CMOS devices have high peak-power currents, which often result in EMI emission problems. This is often a surprise to the designer expecting EMI to go down, thanks to the lower power consumption of CMOS. The solution is to pay attention to the power decoupling.

First, start at the devices. Any component that is clocked (µPs as well as subsequent clocked devices) must be decoupled with a high-frequency capacitor right at the chip. If multiple power and ground pins are provided, each pair must be decoupled. Once again (just in case you missed our earlier warnings), pay particular attention to your high-speed CMOS devices. For EMI control, values in the 0.01- to 0.1-µF range usually work well. Keep the leads short!

Second, decouple at the board entry points. Power-entry decoupling on most boards comprises a 1- to 10-µF bulk decoupling capacitor. The primary function of this capacitor is to recharge the smaller high-frequency capacitor's decoupling circuits on the board. We also like to see a small high-frequency capacitor at the power-entry point, in parallel with the bulk capacitor. This small capacitor's function is to stop any high-frequency noise that may be trying to sneak off the board via the power leads. The bulk capacitor is too inductive to be of much

Fig 5—Align the planes

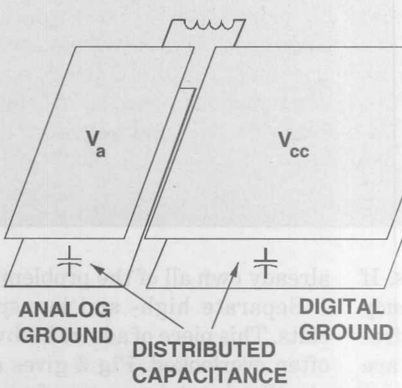


Fig 6—PC-board design

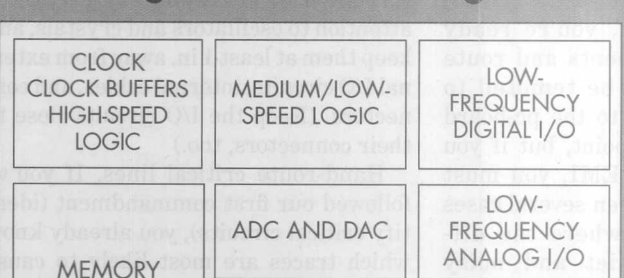


Fig 7—When to terminate

Family	t_r/t_f (nsec)	Distance (in.)	Distance (cm)
GaAs	0.1	0.2	0.5
ECL	0.75	1.5	3.8
Schottky	3	6	15
FAST	3	6	15
AS	3	6	15
AC	4	8	20
ALS	6	12	30
LS	8	16	40
TTL	10	20	50
HC	18	36	90

t_r=rise time of logic family in nsec
t_f=fall time of logic family in nsec
Distances based on 2 in./nsec, or 5 cm/nsec

use at frequencies above about 1 MHz.

Third, keep the capacitor leads short. Capacitor leads have a self-inductance that limits the capacitor's effectiveness at high frequencies. The leads form a series resonant circuit with the capacitor, and, above the resonant frequency, the circuit impedance actually increases with frequency instead of continuing to decrease. This is shown in **Fig 9**, which also gives typical resonant frequencies. As you can see, capacitors become inductive at surprising low frequencies if leads are long.

VI. Pay attention to the connectors

Because connectors connect to the outside world (cables or buses), they represent the last chance to catch EMI before it enters or leaves the pc board. Careful attention to connector details can pay big dividends in controlling EMI at the pc-board level.

Location is crucial. We've already emphasized separating high- and low-speed circuits. Keep in mind that most connectors are hooked to cables, which act as unwanted antennas for EMI. Therefore, keep the connectors as far away as possible from "hot" signal sources, such as clocks, and as far away as possible from vulnerable circuits, such as resets or interrupts.

We've seen too many cases of an RS-232 connector located right next to the µP oscillator. Please, separate them by at least 1 in. or more. Watch out for hot traces too; we had one case where a µC's V_{CC} trace went right through the middle of a connector area. Needless to say, this system was failing emission tests.

Do you have enough grounds? In most systems, connector pins are at a premium. Thus, many designers skimp on the signal returns. The rationale is that "ground is ground," and that only one or two are needed. This approach can cause both serious EMI and operational problems. Remember, every milliampere that leaves the connector must somehow return to its source.

Ideally, you should have a dedicated return for each signal, but this is often not practical. For most systems up to about 20 MHz, we recommend no more than a 5:1 ratio for signals to returns. At frequencies above 20 MHz, it's time to get serious about dedicated returns due to transmission-line effects and the need to control impedance.

Be sure to distribute the signal returns throughout the connector as well. The object is to limit the "loop sizes" on the cables. At frequencies above about 10 kHz, most of the current returns on the smallest loop because it has the lowest inductance. These smaller loops radiate less, and they receive less radiated energy as well. One further idea—route any critical lines (which we identified earlier) next to the return lines to minimize their loop areas. See **Fig 10** for details.

Watch out for internal cable sneak paths. Be careful where you route internal cables. Often, we see a ribbon cable lying directly over the system clock, which then carries clock harmonics all over the system. Although technically not a board issue, this sort of careless routing can cause no end of headaches. Keep your internal cables and the connectors away from all critical circuits and traces.

VII. Pay attention to clocks

By now, it should be apparent that system clocks deserve special attention for EMI emissions. Here are some guidelines we use for clock circuits.

Keep the hot leads short. Crystals, resonators, and oscillator modules should be located as close as possible to the processor. If you're using a 2-layer board, adding a small crosshatched ground plane under the clock or resonator is also a good idea. It's usually better to ground a crystal or oscillator case through a short, direct connection to the circuit ground plane as well.

Watch out for noisy oscillator modules. We prefer crystals to oscillators because they tend to have less harmonic energy. If you do plan to use an oscillator, you may want to try several vendors; some models are much noisier than others. For the same reason, you should not change vendors after you have qualified your equipment for emissions.

Add small series damping resistors to clock outputs. A series resistor in the 10 to 47Ω range in clock output lines often helps reduce ringing with little penalty in rise time. On longer trace runs that start to behave like transmission lines, this series termination also helps control reflections. But even short lines can ring, due to the parasitic circuit capacitance and inductance. We generally determine this experimentally by looking at the voltage waveform on an oscilloscope. The secret is to use just enough resistance to dampen the

Fig 8—Termination techniques

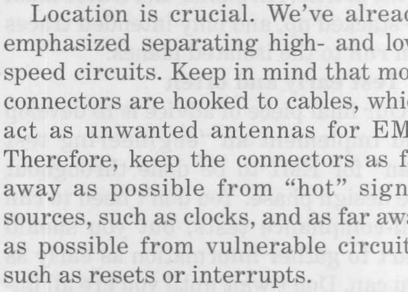
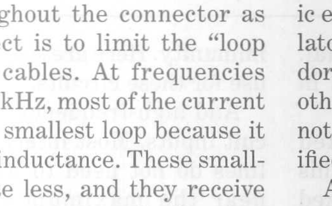


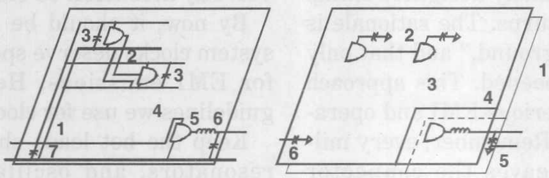
Fig 9—Capacitor resonance



CAPACITANCE (pF)	RESONANT FREQUENCY (MHz) 1/2-IN. LEADS	1/4-IN. LEADS
10,000	16	23
1,000	51	72
500	72	100
100	160	230

COMBINATION CAPACITANCE PLUS INTERNAL AND EXTERNAL LEAD LENGTH:
LARGER CAPACITOR MOVES RESONANT FREQUENCY DOWN WITHOUT PROVIDING ANY HIGH-FREQUENCY IMPROVEMENT

Fig 10—Some quiet designs



Good
1 Parallel power/ground traces
2 Parallel signal/return traces
3 Power decoupling at chip
4 Separation from I/O
5 Separate I/O power
6 High-frequency filter on I/O
7 High-frequency capacitor on power

Better
1 Multilayer board
2 Power decoupling at chip
3 Separation from I/O
4 Isolated I/O power/ground plane
5 High-frequency filter on I/O
6 High-frequency capacitor on power

Daryl's Five-Five rule: Consider multilayer boards with clock rates above 5 MHz, or edge rates below 5 nsec.

ringing and not destroy the signal. Small ferrite beads also work well in this application.

Decouple the V_{CC} on all clocked devices. We can not overemphasize this precaution. Remember, every clocked device is gulping current at the clock frequency, so the V_{CC} lines radiate just like a signal line. In extreme cases, we like to add a small ferrite bead in series with the V_{CC} line. This works very well on 2-layer boards where the high-frequency power distribution is not too good to begin with. Incidentally, clocked devices should never be on the same IC that has any type of I/O signal, even if the I/O line runs at dc. We've seen several cases where control or signal lines were modulated by clock noise in the IC package.

Control the clock routing. Hand-route your clock lines and keep them away from I/O circuits. On 2-layer boards, consider adding a dedicated signal return; the clock now is fed from a "transmission line" rather than an unwanted "antenna." In extreme cases, you can even add a return on both sides of the clock signal line. These guard traces help control unwanted crosstalk between the clock trace and other traces.

VIII. Pay attention to resets

Reset lines, interrupts, and control lines deserve special attention for immunity. Here are some guidelines we use for these circuits.

Add high-frequency filtering at circuit inputs. Most interrupts and reset lines do not need to work at or even near the maximum circuit speed. Therefore, adding a small amount of high-frequency filtering to these inputs can eliminate a lot of unwanted and unexpected resets or interrupts. You should add this filtering even if you have a big (1- to 10-µf) capacitor for the reset. Big capacitors look inductive to high-speed transients, so additional high-frequency filtering is still needed.

Watch the trace routing. Keep these critical lines away from other fast circuits (which can cause false switching due to crosstalk) and away from I/O circuits (external noise may couple to these lines). We also like to keep critical lines away from board edges.

IX. Pay attention to I/O circuits

Because I/O circuits connect to the outside world, they deserve special attention when you are laying out your circuit board.

Three sneak paths are power, ground, and signal. These sneak paths were illustrated in **Fig 1**. High-frequency noise can be coupled onto a low-frequency I/O signal through several paths. It can couple directly through the signal path or it can couple indirectly through "modulation" of the power or ground. Finally, noise can also couple through parasitic capacitance, or crosstalk.

Thus, you may need to add high-frequency decoupling of the I/O circuitry's power and ground and high-frequency filtering of the signal lines. Remember, this is your last chance to catch the energy before it leaves the system. I/O-coupled noise is a major source of EMI problems. Too often we see these circuits neglected to save a few cents, only to cost thousands of dollars in rework and retest.

What about isolated I/O planes? This technique is becoming popular and done correctly can be very effective. It is particularly useful in keeping the I/O power and ground clean. Just remember the chain-saw law we discussed earlier in the article. All planes and traces must be stacked up, and only intended traces can run to the isolated planes.

X. Test early and often

Our final piece of advice is to develop and implement an "engineering test plan" for EMI to be done throughout the design phase. You don't need to run full-compliance tests, but you should start to gather information as early as you can. Don't wait until you are all finished with the prototypes to do your EMI testing, as problems there will likely be painful and expensive.

If you need to pass emission requirements, you should run a quick emission test on your first prototype. The system need not work, as long as the clocks are functional. This gives you a chance to find any gross errors and can help you develop a profile of your system. We did this on a system several years ago and uncovered a potential EMI disaster when it was still easy to fix.

If you need to pass immunity requirements, you should run quick tests on prototypes as well. At this stage, the system should be functional, however, because you need to be able to recognize a failure. The system need not be fully functional however, and often it makes sense to develop special test software for immunity tests. We'll discuss some of our favorite engineering-lab tests in a later chapter. EDN

That's it for our session on pc boards. **Fig 10** shows some "quiet" reference designs, incorporating many of the techniques discussed in this article. This list is by no means all-inclusive, but we hope we've helped you recognize some of the more common EMI pitfalls. We've seen that, by focusing on a few key areas, you can make your circuit boards both more EMI-immune and EMI-quiet. These circuit concepts work—nowhere else can you achieve so much EMI integrity with so little cost. Even so, we often cannot do everything at the board level. In the next chapter, we'll look at shielding, or how to contain or block EMI before it gets to the circuit level.

Key points

All EMI problems begin and end at a circuit

- Source suppression for emissions
- Circuit hardening for immunity
- Circuit-board prevention=cost-effective EMI control

10 EMI commandments for circuit-board design

I) Identify critical circuits
- Emissions—clocks, buses, and other repetitive circuits
- Immunity—resets, interrupts, and critical control lines

II) Choose devices with EMI in mind
- Slower is better—rise times and clocks
- Watch out for high-speed CMOS—both signal and power

III) Choose a board design
- Multilayer boards 10 to 100 times better for both emissions and immunity
- Five-five rule—use multilayer board for clock >5 MHz or rise time <5 nsec
- Chain-saw law—use for divided planes
- Don't embed traces in power or ground planes

IV) Do the initial layout
- Separate high- and low-speed sections
- Keep critical circuits away from I/O circuits
- Hand-route critical lines
- Terminate traces based on 2-in./nsec rule

V) Pay attention to power decoupling
- Decouple every device with high-frequency capacitor
- Decouple every power input to board with high-frequency capacitor
- Keep capacitor leads short

VI) Pay attention to the connectors
- Keep critical circuits away from connectors
- Use adequate ground returns (5:1 minimum for high-frequency circuits)
- Watch out for internal-cable sneak paths

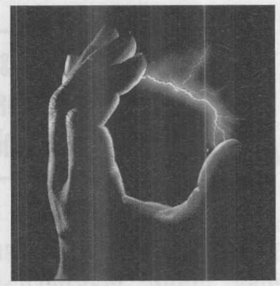
VII) Special concerns for clocks
- Keep the hot leads short
- Add small damping resistors or ferrites to clock outputs
- Control clock routing
- Watch out for noisy oscillator modules

VIII) Special concerns for resets, interrupts, and control lines
- Add high-frequency filtering at circuit inputs
- Control trace routing

IX) Special concerns for I/O circuits
- Three EMI paths through I/O—signal, power, and ground
- Add high-frequency filtering to all I/O lines—even slow I/O
- Isolated I/O planes can help but must be done right

X) Test early and often
- *Don't wait until the end to do the EMI testing*
- Develop and implement your own engineering-level EMI testing
- Objective is to improve probability for success in compliance tests

An ounce of EMI prevention is worth a pound of shielding



The Designer's Guide to Electromagnetic Compatibility

Chapter 7

Shielding for EMI control... and how to do it right

Many designers consider shielding a mechanical issue, not an electrical issue. Let the mechanical engineers worry about shielding, right? But, as we'll see in this article, shielding is also an electrical issue, and it is a very important weapon in our battle against EMI.

Many systems today require at least some shielding for proper operation or to meet EMI requirements for emissions and immunity. As circuit speeds and sensitivities increase, so will the need for shielding. Source suppression or circuit hardening may not be enough—you may need to provide a defensive barrier to contain or block the EMI as well.

Shielding can be applied at many levels, from individual circuits to systems to fully enclosed rooms. Regardless of the size, the physics of shielding remain the same. It's important to know how shielding works and how it fails. (It's easy to build a good shield, but it's even easier to destroy it.)

In this chapter, we'll show you how to design shields that avoid the most common mistakes. We'll briefly review the physics of shielding, and then we'll give you a set of shielding-design guidelines. These guidelines are based on the most common shielding blunders we encounter as EMI design engineers.

Determine your needs

Before you design a shield, you need to know your objectives. How much shielding do I need, and how do I measure or predict it? The two key parameters are frequency and attenuation. These are often combined into a single term, "shielding effectiveness," which is defined as follows:

$$SE\ (dB) = 20 \log F1/F2,$$

where F1 and F2 are the field strengths of the attenuated and incident waves, respectively.

Shielding effectiveness is expressed in decibels (usually as a function of frequency) and is always positive (or zero). The higher the number, the better the shielding properties.

Most of today's systems require at least *some* shielding for proper operation.

You can determine your system's shielding effectiveness needs experimentally or you can estimate them. In some cases, you'll know the exact needs. For example, if you've failed an FCC test by 12 dB at 220 MHz and 6 dB at 350 MHz, you know that you need at least that much shielding to pass the test. (This assumes that cables aren't the problem, which we'll discuss in the next chapter.) Incidentally, we usually focus on the highest frequency of concern; if we provide enough shielding at the higher frequencies, the lower frequencies usually take care of themselves.

If you are just beginning a design, here are some quick rules of thumb we use:

Commercial design—emissions: 40 to 60 dB, frequency range: 30 MHz to 20 times the clock frequency.

Commercial design—immunity: 40 to 80 dB, frequency range: 25 to 500 MHz.

Military design—emissions and immunity: 80 to 100 dB, frequency range: 10 kHz to 10 GHz or more.

These estimates can be refined by testing an unshielded unit and then determining the actual margins the shielding must provide. Most of the time, however, these guidelines should be adequate for you to begin your design.

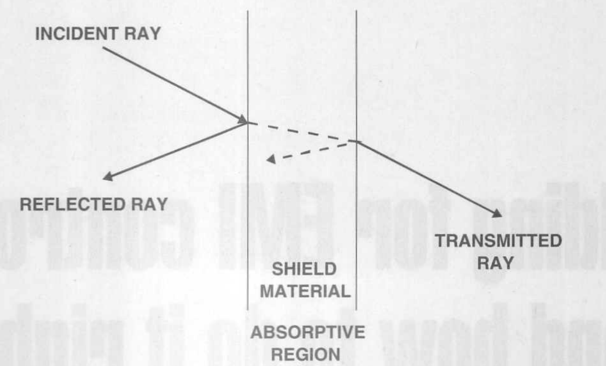
There is a special shielding case we need to address: low-frequency magnetic fields. The primary concern here is containing emissions from power transformers, power supplies, magnetic-deflection circuitry, and other devices using high current at low frequencies. A secondary concern is immunity against such fields. As we'll see later in this article, it can be very difficult to shield against these low-frequency/low-impedance fields so it is important to know whether this is a requirement for your equipment.

Regulatory bodies are divided on the need to limit magnetic-field emissions. Such a requirement exists but is often waived in military systems, depending on the application. For commercial equipment, only VDE requires magnetic-field emissions tests. Neither the FCC nor the European Community require magnetic-field emission tests. It does

appear, however, that both Europe and the United States may adopt magnetic-field emission limits for video display terminals because of the hysteria over the possible biological effects of low-frequency magnetic fields. If such regulations are adopted, magnetic-field shielding will become a very important issue for many equipment designers, particularly those designing display terminals and, perhaps, power supplies.

The majority of our shielding concerns however, will be in the upper radio-frequency range (30 to 1000 MHz) to meet the FCC, VDE, European Community and other international electric-field emission and immunity requirements.

Fig 1—Shielding model



How shielding works

Our objective here is to keep things simple and to give you a quick overview without getting bogged down in the mathematics. (For those of you who actually like long and detailed equations, we can recommend some EMI texts that include all the shielding equations in gruesome detail.) Fortunately, you don't need to understand electromagnetic-field theory to understand shielding. Much of it is common sense, once you understand the underlying principles. We'll start with solid materials because no shield can perform better than the material from which it's made. Then we'll move on to openings and penetrations and how to deal with them.

As we'll see, most high-frequency shielding problems are caused by openings in materials, not the material itself. Most conductive materials (such as aluminum, steel, and copper) provide more than enough shielding for most EMI applications. For example, at frequencies from 30 to 1000 MHz (our main concern for commercial designs), even aluminum foil exceeds 90 dB of shielding effectiveness, which is more than adequate for most commercial designs. Unfortunately, this same aluminum foil is woefully inadequate against low-frequency magnetic fields where you need thick steel or highly permeable materials.

There are two principal shielding mechanisms: reflection and absorption. This is illustrated in **Fig 1**, which shows how a shield affects an electromagnetic field. This model, which has been around for many years, uses a transmission-line approach rather than an electromagnetic-field-theory approach. It's simple, it works quite well, and it's a big help in understanding some rather diverse and interesting phenomena.

Two things happen when an electromagnetic wave traveling through space encounters a shield. First, much of the energy is reflected, just as if a "short" had been encountered on a transmission line. Second, energy that is not reflected is then absorbed by the shield. Only the residual energy emerges from the other side of the shield. These two effects are independent, but they combine with each other to multiply the shield's effectiveness. This phenomenon is commonly expressed as follows:

$$SE\ (dB) = R\ (dB) + A\ (dB)$$

where SE is the shielding effectiveness in decibels, R is the reflection loss in decibels, and A is the absorption loss in decibels. (Remember, adding the decibels is the same as multiplying the two factors.)

A third factor, called "re-reflection," comes into play for very thin shields. These secondary reflections (often referred to as the "B-factor") decrease the shielding effectiveness you expect from simple reflection and absorption. Because this factor affects only very thin shields, we usually just ignore the B-factor when designing shields.

We'll soon see that reflection is the key mechanism for high-frequency RF shielding (FCC/VDE emissions or IEC 801.3 immunity) and that a thin conductive shield (aluminum foil or even conductive paints) provide very high levels of RF shielding. We'll also see that absorption is the key mechanism for low-frequency magnetic-field shielding (for power-supply and video-display-terminal emissions and some MIL-STD-461 tests) and that you need thick steel shields (or other permeable materials) to provide even moderate amounts of low-frequency magnetic-field shielding.

Three types of fields

It is customary to use three types of "fields" to explain shielding. These three fields account for differences in reflection losses due to distance and frequency. They also explain why the same shield can behave very differently for different energy sources. The three field types are:

Plane wave fields—If you are located greater than about one-sixth of a wavelength from the source, the wave impedance (ratio of electric field to magnetic field) is a constant 377V in free space or air. This field is therefore known as the "far field," or the "radiation field," because "real energy" predominates here and propagates as a "plane wave." (Remember Maxwell's equations? And you thought you could read about electromagnetic shielding without even at least hearing his name mentioned?)

Most external RF sources are plane waves. At 30 MHz, a wavelength is 10m, so any transmitter more than about 2m away is in the far field. At 1000 GHz, this distance is only about 5 cm. Plane-wave shielding predicts how well a shield will perform against external threats, such as radio transmitters or IEC 801.3 RF-immunity tests.

Electric fields—If you are close (less than one-sixth of a wavelength) to a high-impedance source, the wave

Fig 2—Shielding curves for copper

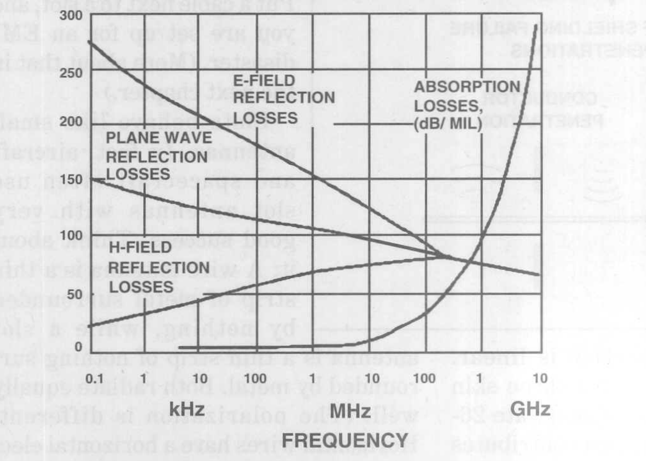
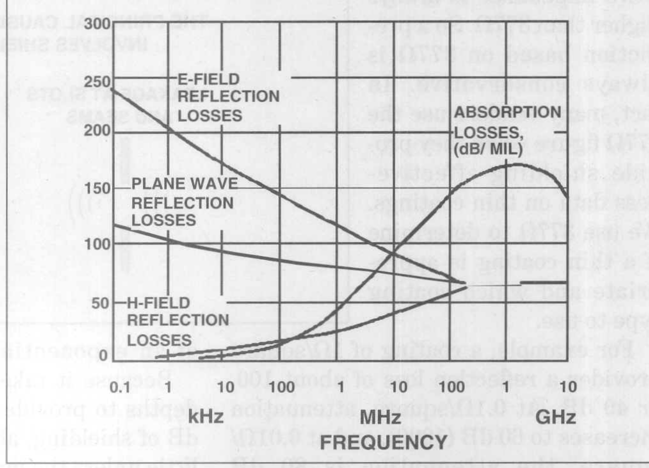


Fig 3—Shielding curves for steel



impedance is greater than 377V and approaches the circuit impedance as you move closer to the source. This is known as the "near field," and capacitive (reactive) energy predominates. As we'll soon see, near-field reflection losses are greater because of the higher wave impedance.

Higher reflection losses are good news because most internal circuits are in the near field, and many of these circuits generate "electric fields," giving us some bonus shielding. Electric-field shielding is often used to predict how well a shield performs against internal high-frequency threats, such as high-speed circuits.

Magnetic Fields—If you are close (less than one-sixth of a wavelength) to a low-impedance source, the wave impedance is less than 377V and approaches the circuit impedance as we move closer to the source. This is also the near field, but in these cases, inductive (reactive) energy predominates.

As we'll soon see, reflection losses are much less in these situations because of the lower wave impedance. This is double bad news because, as you go lower in frequency, you become closer to the source in terms of wavelengths and eventually reach a point where a barrier provides virtually no reflection at all. Furthermore, low frequencies also mean that a shield provides less absorption *for a given material thickness.* Mother nature really punishes us here.

Magnetic-field shielding is often used to predict how well (or, more likely, how poorly) a shield performs against both internal low-frequency threats, such as power supplies and deflection circuits, and external low-frequency threats, such as nearby power transformers and other magnetic-field sources. The bottom line: Low-frequency magnetic-field shielding is tough to achieve, so circuit suppression and hardening methods become very important. (At lower frequencies, you need steel or other high-permeability shielding; even 0.25-in. aluminum is virtually transparent to 60-Hz magnetic fields.)

Fig 2 (for copper) and **Fig 3** (for steel) show examples of shielding provided against these three types of fields. As you can see, even thin layers of copper or steel provide high shielding levels at high frequencies but for low-frequency magnetic fields, you need thick steel to absorb the energy. (Copper shielding is only a little bit better than aluminum, so you can use **Fig 2** to approximate aluminum as well.)

You sometimes see these types of shielding curves published, and some dyed-in-the-wool EMI types may even want you to calculate these values. If you do, it's best to use a computer because the equations can get really ugly. We know; we've even calculated them using a slide rule. (Remember those?) Frankly, though, we usually don't bother with the detailed calculations. As designers, we just want to know where the shields work and where they don't. Now lets look at both reflection and absorption in a bit more detail.

Reflection losses are caused by an impedance mismatch between the incident wave and the shield surface (often called the barrier.) The greater this impedance mismatch, the better the reflection loss. A simple approximation for the reflection loss (R) of highly conductive shields is given by the following expression:

$$R\ (\text{dB}) = 20\ \log(Z_w/4Z_b)$$

where R is the reflection loss in dB, Z_w is the wave impedance in ohms (electric field divided by magnetic field), and Z_b is the barrier impedance in ohms/square.

Maximum reflection occurs when Z_w is high and Z_b is low. For thin shields (less than a few skin depths), reflection is the key shielding mechanism.

Note the unit ohms/square for the barrier impedance. No, this isn't a mistake. It's the impedance across the opposite sides of a square (series resistance increases at the same rate that parallel resistance decreases—thus, ohms/square). Conductive coatings such as paints are often specified in ohms/square for a given thickness, and the specs typically range from 0.01 to 1 V/square. If you know the wave impedance, you can thus easily determine the reflection loss.

So what is the wave impedance? When far from the source, the answer is easy: it's 377Ω, the impedance of a plane wave in free space. Actually, this is not a bad approximation for electric-

field shielding because the wave impedance is always higher than 377Ω. So a prediction based on 377Ω is always conservative. In fact, many vendors use the 377Ω figure when they provide shielding-effectiveness data on thin coatings. We use 377Ω to determine if a thin coating is appropriate and which coating type to use.

For example, a coating of 1Ω/square provides a reflection loss of about 100, or 40 dB. At 0.1Ω/square, attenuation increases to 60 dB (1000), and at 0.01Ω/square, the attenuation is 80 dB (10,000). These values are well within the range we need for commercial designs, although they are on the light side for military designs. So, thin conductive coatings can provide very significant amounts of shielding against both internal (emissions) and external RF threats (immunity). Remember, however, that this same thin shield is useless against low- frequency magnetic fields.

Absorption losses are caused by an exponential decrease in shield current through the thickness of the shield material due to skin depths. This is very similar to heat loss through insulation in a wall. Two material properties primarily affect absorption losses: the material's conductivity and its permeability. The more conductive the material and the higher the permeability, the higher the absorption losses. Absorption losses are independent of distance between the shield and source.

A simple expression for absorption loss is given by the following expression:

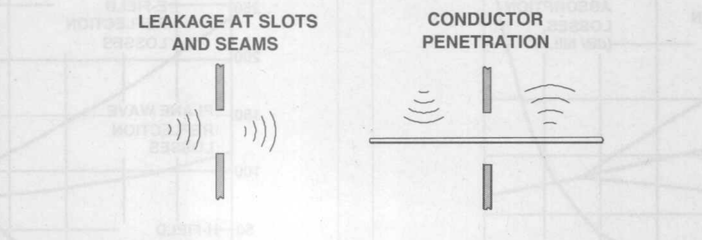
$$A(dB)=8.68(SD)$$

where SD (skin depth) = $\sqrt{\mu\rho t}$, μ is the material's permeability, ρ is the material's conductivity, and t is the material's thickness.

Material thickness, conductivity, and permeability all contribute to skin depth and thus to absorption losses. Note there is no "20-log" term in this equation because skin depths are exponential and the logarithm of an exponential function is linear.

Fig 4—Slots and penetrations

THE PRINCIPAL CAUSE OF SHIELDING FAILURE INVOLVES SHIELD PENETRATIONS



Because it takes at least three skin depths to provide even a moderate 26-dB of shielding, absorption contributes little unless the materials are "thick" or the frequencies are high. For example, .001-in. aluminum foil has almost no absorption at frequencies under 100 MHz, and even 0.1-in. aluminum has no absorption below 1 kHz.

The good news is that absorption enhances high-frequency shielding, which is usually high to begin with. The bad news is that absorption is all we have to work with on low-frequency/low-impedance shielding be-cause there is virtually no reflection for low-frequency magnetic fields. You must absorb low-frequency magnetic-field energy with steel or other highly permeable materials.

Two ways to destroy a shield

While it's relatively easy to provide a lot of high-frequency shielding with inexpensive materials, it's also very easy to destroy most of that shielding. We've seen many cases where poor design turned a good 100-dB shield into a 20-dB shielding wimp. The two shielding killers are slots and penetrations, as shown in **Fig 4**.

Slots—Intuition tells us that any opening in a shield can leak, much like an open window can cause heat loss in a building. The surprise is that for electromagnetic leakage, the longest dimension of the opening is critical, not the total area. A 10×1/10-in. slot will be about 10 times more leaky than a 1×1-in. square hole, even if both have the same area.

And that slot may not even be obvious; it could be a painted seam or cover or a poorly fitting panel or door. Put a cable next to a slot, and you are set up for an EMI disaster. (More about that in the next chapter.)

Slots behave like small antennas. In fact, aircraft and spacecraft often use slot antennas with very good success. Think about it: A wire antenna is a thin strip of metal surrounded by nothing, while a slot antenna is a thin strip of nothing surrounded by metal. Both radiate equally well. (The polarization is different. Horizontal wires have a horizontal electric field while a horizontal slot has a vertical electric field.)

Because slots are small antennas, we can estimate their leakage as follows:

$$SE = 20 \log(150/FL)$$

where F is the radiated frequency in megahertz and L is the slot length in meters.

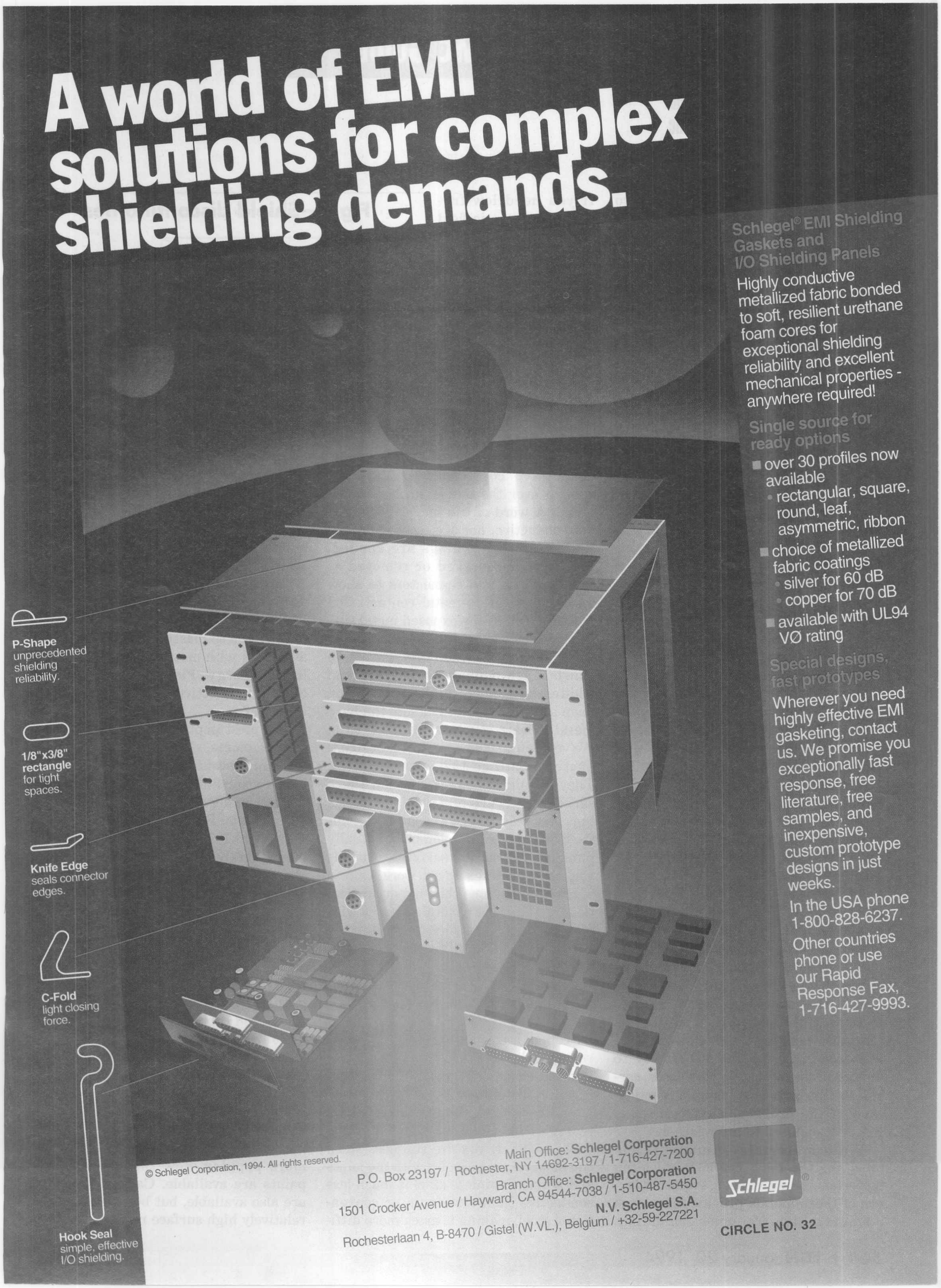
For example, a 15-cm slot (about 6 in.) provides only 20 dB of attenuation at 100 MHz and provides zero attenuation at 1 GHz.

As a rule of thumb, we like to keep slots shorter than 1/20 of a wavelength at the highest frequency of concern. Here are some examples:

Frequency	Maximum slot length
100 MHz	15 cm (about 6 in.)
300 MHz	5 cm (about 2 in.)
1000 MHz	1.5 cm (about 5/8 in.)

These maximum allowable dimensions assure you of at least 20 dB of attenuation at the highest frequency, which is about the minimum attenuation worth shooting for. If you need 40 dB of attenuation, you then need to keep slots shorter than 1/200 of a wavelength, or 1/10 of the dimensions in the three above examples.

Penetrations—The other destroyer of shields is unterminated metal passing through the shield. Dimensions don't matter here; even a pinhole with an insulated wire running through it can carry large amounts of energy through the shield. That's because the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penetration and the shield form the two sides of a transmission line that propagates the energy through the hole in the shield.

Penetrations can be intentional conductors, such as signal and power lines or unterminated cable shields. They can also be unintentional conductors, such as control shafts. We've even seen leakage due to water coolant carried in rubber hoses (most water is slightly conductive). We've also seen shielding reductions of 40 dB or more caused by a single unterminated penetration.

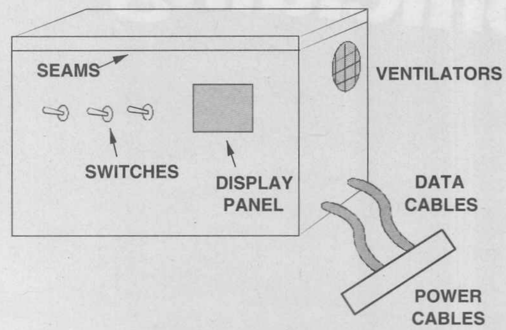
For those of you interested in electronic espionage, the following technique has destroyed the integrity of many electronically shielded rooms. Here is an experiment you can try to demonstrate this concept. The next time you are in a shielded room, take an FM radio inside, and shut the door. You should hear almost nothing. Now run a wire or cable through one of the access ports (usually a piece of pipe), or connect two pieces of unshielded wire to both sides of a feedthrough connector. If you are in a screened room, just run a 2- or 3-ft piece of insulated wire through the screen. You should have no problem hearing the radio now. We once heard of a new hire at an EMC test lab who discovered he could listen to his radio if he did this.

Now that we've covered the physics of shielding and discussed the problems, let's look at how to design good electromagnetic shields. Most of our focus will be on RF shielding in the 30- to 1000-MHz range.

(1) Select the right materials. Most electronic enclosures today are either metal or plastic. If the enclosure is metal, the key shielding issues are usually the seams, openings, and penetrations. If the enclosure is plastic, you must also consider the shielding material's conductivity and its ability to adhere to the plastic. In both cases, corrosion may also be a concern, particularly if the intended environment is harsh or exposed to the weather.

Solid materials—Aluminum and steel are the most common shielding materials. As we've seen, even thin layers of these metals provide more than adequate high-frequency shielding.

Fig 5—Shield discontinuities



If you need low-frequency magnetic-field shielding, then you should use steel. Aluminum is virtually transparent to low-frequency (under-1-kHz) magnetic fields.

Corrosion is a problem. Steel rusts, and aluminum oxidizes to form a hard, nonconductive film over the metal. You must protect both metals with a conductive coating, which can be applied over the entire surface of the metal. A word of caution: anodizing is not conductive, nor are most paints. If these types of coatings are applied, they must be masked or removed at seams, joints, and connectors to allow for clean metal-to-metal contact. You must then treat the exposed metal surfaces with a conductive coating.

For corrosion protection, chromate finishes are popular with steel, and iridites are popular on aluminum. Both form a thin film that protects the base metal. These coatings must be thin. We've seen problems when these conductive coatings that are too thick. They should appear clear, and there should be no runs or drips in the coating. Actually, these coatings are not very conductive, and you must actually puncture the mating surfaces, which is why thick coatings do not work.

For military or other harsh applications, you can plate metal surfaces with nickel, tin, or even silver. Nickel or tin are usually preferred for their low cost and excellent corrosion characteristics. Once again, only the mating surfaces need this treatment; the rest can be painted. For small local shields, beryllium copper is often used. This material is very popular for gaskets because it has low-corrosion, high-conductivity, and excellent mechanical characteristics.

Stainless steel is a popular shielding material for industrial and medical applications. If you use stainless steel, you must be very careful with the joints and seams. Stainless steel is much less conductive than aluminum or conventional steel, making it much more difficult to maintain a low-impedance joint. We've seen several shielding problems with stainless-steel enclosures. If you use stainless steel, you should use high-quality EMI gaskets or, better yet, weld the seams.

Coated materials—Plastic enclosures are very popular today, particularly for commercial products. Unfortunately, unless plastic is heavily loaded and laced with metal, it is transparent to RF energy. Plastic enclosures require a conductive coating to provide shielding.

The most popular coatings are conductive paints, electroless plating, and vacuum deposition. These coatings provide 40 to 80 dB of shielding, which is more than adequate for most commercial designs. Because military designs often need 100 dB of shielding or more, they still rely on metal enclosures. Arc-sprayed zinc was a popular coating in the past but is no longer widely used. Zinc is difficult to apply, the fumes are dangerous, and the zinc tends to flake off if misapplied.

Conductive paints are now widely used as conductive coatings. The most popular EMI paints contain nickel or passivated copper. Both types offer 40 to 60 dB of plane-wave shielding with minimal fuss and expense. Silver paints can provide up to 80 dB of shielding, but they are quite a bit more expensive. Nickel is a favorite in the EMI world, because of nickel's superior corrosion resistance, but copper is becoming more popular, now that passivated paints are available. Carbon coatings are also available, but because of their relatively high surface resistance, they

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do not offer much EMI shielding. In our opinion, graphite coatings are best suited as ESD drains and are not useful as EMI shields.

Electroless plating has become quite popular in the PC industry. In this process, the plastic is first etched with an oxidizing solution that creates micropores in the plastic. When the plastic is then dipped in a copper or nickel solution, a thin layer of metal adheres to the surface. The resulting surface is electrically tight and continuous, and it creates a 60- to 80-dB EMI shield. Some vendors employ an undercoat of copper for high conductivity and an overcoat of nickel for corrosion protection. These combinations hold up very well in salt-spray tests and should work well in moderately corrosive environments.

Vacuum deposition has been used for years to make decorative plastics, such as automotive parts. In recent years, vacuum deposition has moved into the EMI arena with good success. In this process, a metallic film is deposited by evaporating metal in a high vacuum. Several years ago, we tested samples of this process and were impressed with the results (60 to 80 dB of shielding). Other tests, however, show that vacuum deposition can degrade in a corrosive environment. This process is very cost-effective, however, and it is popular for consumer items such as computers and cellular telephones.

Conductive plastic—We do not favor this approach unless the shielding needs are low (20 to 40 dB). Carbon-loaded plastic works very well as a static drain, but, like carbon paint, the surface impedance is way too high to provide much EMI shielding. This technology has not lived up to its original promise, although we may see breakthroughs in the future. We have seen moderate results with plastic that is loaded with interlocking metal fibers, much like an old-fashioned scouring pad. You still need special inserts in the housing to make contact with the metal fibers, and seams can be a problem.

A word of caution on any of these conductive treatments: Thin coatings cannot carry large currents, such as power-fault currents. Unlike metal enclosures, you should not depend on the coatings for a safety ground unless they have been specifically approved by the appropriate safety agency. You may need separate "green-wire" grounds or bonding straps that can carry the necessary fault currents.

(2) Seal the openings

As we stressed earlier, apertures and seams kill shielding. Unfortunately, almost every electronic enclosure has seams, openings, controls, indicators, and ports for cables and connectors. (We had one client who did not have this problem. He built rockets. If you build rockets, you can skip this next section. The rest of you, read on.) **Fig 5** illustrates these typical shield discontinuities.

Large openings—Large openings include viewing ports (CRTs and indicators) and ventilation ports. These large openings create major shielding leaks, but, fortunately, with a little care, you can plug the leaks.

One method of plugging big leaking holes is to break the large hole into many smaller holes. You can do this with screening or by using a pattern of small holes in the metal surface to create the required opening. These smaller holes need not be that small—even holes as large as ¼-in. provide more than 30 dB of attenuation at 1 GHz and more than 50 dB at 100 MHz.

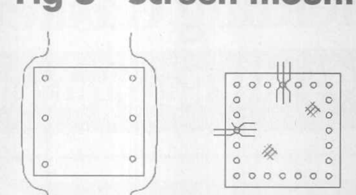
Of course, even smaller holes provide even better performance, and EMI screens with hole spacing similar to window screens are good for 60 to 80 dB of shielding at frequencies to 1 GHz. A key parameter is the screen's wire spacing or hole diameter—the finer the spacing or smaller the hole, the better the shielding. Incidentally, don't use slots for ventilation—use holes. The holes do impede airflow more than slots do, so you will need greater cross-sectional area. Nevertheless, it's worth it to maintain shielding integrity.

A second way to plug big holes is to cover the large hole with a metal-plated glass or plastic cover. You need to make a tradeoff between visibility and shielding effectiveness, but you should be able to obtain at least 40 dB up to 1 GHz. A key parameter is the surface conductivity of the plating or coating—the lower the better. A 1-Ω/m coating provides 40 dB of shielding for plane waves, and, at 0.1Ω/m, the attenuation reaches 60 dB for plane waves.

A third hole-plugging method is to cover the large hole with a metal "honeycomb" panel. This technique is often used for ventilation ports when very high levels of shielding are needed. The "depth" of the holes provides additional attenuation due to waveguide effects. You can obtain shielding over 100 dB when these panels are properly installed. These are not seen much in commercial equipment but are often used in military systems and in shielded rooms. Honeycomb panels also present much lower resistance to airflow than does a simple perforated panel, which can help with ventilation.

Proper installation is crucial for all of these methods. You must provide a tight RF seal around the perimeter, as shown in **Fig 6.** A tight seal means continuous metal-to-metal contact. Four screws in the corners are not enough. Bonding the surfaces of the plug and panel together with a gasket or conductive caulking is the preferred approach. Otherwise, your 40- to 100-dB solution is reduced to 20 dB or less. Incidentally, we advise against combining EMI screens with dust filters. Sooner or later, the dust filter will be misinstalled, destroying the EMI shield.

Fig 6—Screen mounting



Seams—Seams include mechanical joints and mating members, such as covers and door panels. Seams create slot antennas that can leak EMI as much as the larger openings we just discussed. Remember, it's the longest dimension of the opening that is critical, not the total area. You need to seal

these leaks just as you do any other opening.

One seam-sealing method is to break up the slots with screws. These guarantee at least minimal spacing between the metal-to-metal contact points because the fasteners buckle and warp the metal panels. This is shown in **Fig 7**. Of course, if the panels are painted, you don't get any metal-to-metal contact anyway, so keep paint out of the seam.

Screw spacing provides effective shielding up to about 100 MHz. At this frequency, spacing the screws 6 in. apart (1⁄20 wavelength) yields 20 dB of attenuation through the slot. To maintain 20 dB at 300 MHz, the required spacing drops to 2 in., which is not very practical. For higher frequencies (or higher attenuation levels), you need to use other methods. (Note: screw threads alone do not provide adequate metal-to-metal contact at high frequencies; conductive mating of the two surfaces is required. The same condition applies to hinges, too.)

You can use gaskets to seal the seams, either continuously or in sections. For commercial designs, you can use gasketing strips or patches to break up or control slots, as shown in **Fig 8**. For military and other high-performance designs, the gaskets should be continuous to meet the higher shielding needs. Be sure the gaskets mate with clean metal surfaces. Putting a gasket between painted or anodized surfaces wastes time and money. You should protect the clean metal against corrosion, as discussed earlier in the article.

Interlocking metal surfaces are another method of sealing seams. Many personal computers now use tongue-and-groove slides on covers. Auto radios and television tuners also use this approach. Just because you are designing a high-volume, cost-sensitive product doesn't mean you can't have good shielding. Clever engineering pays big dividends here.

The surefire method for sealing seams is to weld them. Don't overlook this possibility. We had one client who struggled through several iterations of FCC and VDE testing with a multipanel box that leaked RF energy like a sieve. When the client finally went to a simple welded box, the company's RF problems almost vanished. As we mentioned earlier, it's very important to weld stainless steel because the material's conductivity is much lower than that of conventional steel or aluminum.

Gaskets—No discussion of shielding would be complete without discussing EMI gaskets. Like any other type of gasket, the EMI gaskets fill a void—in this case, with a conductor. Of course, that conductor must mate with a conductive surface, as we cautioned earlier.

There are four popular types of EMI shielding gaskets: beryllium copper, wire mesh, conductive elastomers, and conductive cloth-over-foam. Each has pros and cons, depending on its applications.

Beryllium-copper gaskets offer the best EMI performance, often exceeding 100 dB. This material has very high conductivity and good corrosion characteristics. It is also very springy and takes very little mechanical "set," making it ideal for doors and access panels. You can form beryllium copper into many shapes, including finger stock, spirals, and serrated surfaces. You can plate beryllium copper for even better EMI performance. The drawbacks are cost, vulnerability to damage, and lack of an environmental seal.

Wire mesh gaskets offer very good EMI performance, often close to that of finger stock. Most wire mesh takes a set and thus is not intended to be reused. It's fine for permanent seals but is not suitable for doors and panels that will be opened and closed. Like fingerstock, you can plate wire mesh. The drawbacks are the tendency to take a mechanical set, moderate to high compression forces, and the lack of an environmental seal.

Conductive elastomers offer good EMI performance, but not as good as fingerstock or wire mesh. However, you can use these gaskets to provide an environmental seal as well as an RF seal. You can form gaskets made of conductive elastomers into many shapes and forms. The main drawback is the high compression force needed with solid elastomer gaskets but hollow gaskets, can often overcome this problem.

Conductive cloth-over-foam gaskets are relative newcomers to the EMI game, but they are quite effective. Most use a silverplated cloth over an open cell foam to create a soft gasket that can take up a lot of slack space. These gaskets are quite popular in commercial applications for racks and door panels. The drawbacks are the lack of an environmental seal and some abrasion after repeated use.

Fig 7—Screw placement

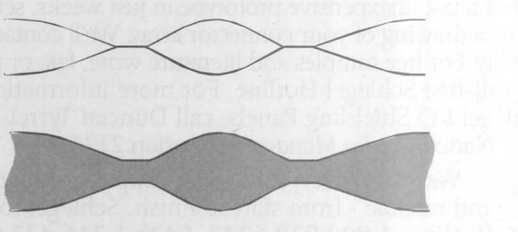


Fig 8—Gasket placement

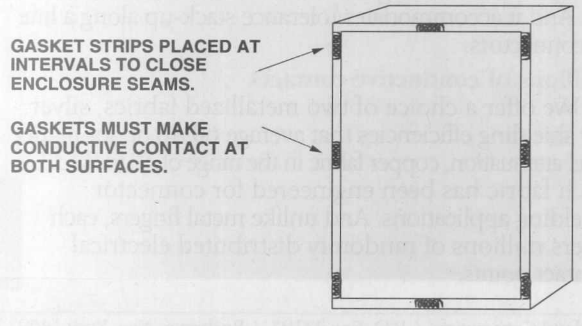


Fig 9—Cable penetrations

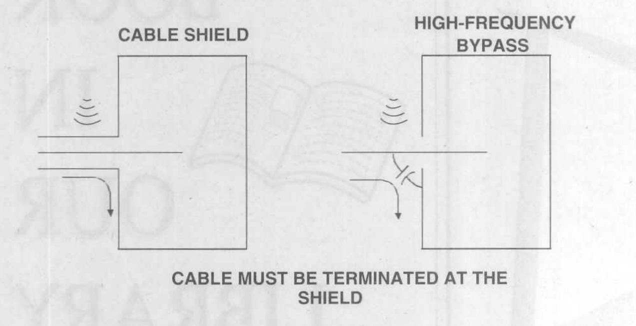
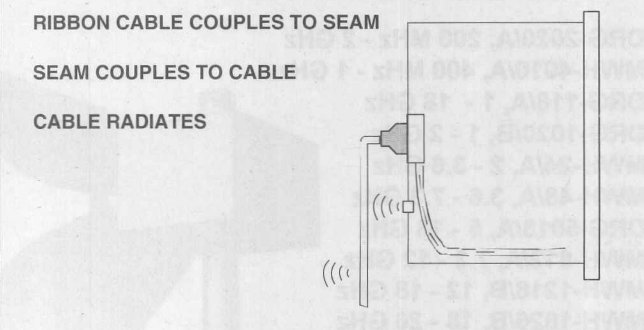


Fig 10—Devastating problem



EMI gaskets are very popular for today's high-speed systems, and gasket technology continues to advance. If you are designing a system faster than 20 MHz or if you are worried about ESD or RF immunity, you should use gaskets to seal your seams. All EMI gaskets work very well when properly applied, so the decision of which to use is driven primarily by mechanical, not electrical, design issues.

(3) Protect the penetrations

Fig 9 shows several typical penetrations and how to protect them from EMI.

Cable shields—You need to circumferentially bond cable shields to ground to prevent currents from riding through the shield. For connectors, this means maintaining a continuous seal from the cable shield, to the connector backshell, to the mating connector, to the chassis. Avoid pigtails, those nasty little ground wires for cable shields that cause so many EMI and ESD problems. You'll read about cables and connectors in more detail in the next chapter.

Power and signal lines—Unshielded power and signal lines penetrating the shield must be filtered at (or very near) the point of shield penetration. Feedthrough filters work best, but they're expensive. High-frequency filters close to the penetration are often adequate for commercial designs. For military and other high-performance designs, use the feedthrough filters.

Shafts and indicators—Control shafts and indicators can provide sneak penetrations through the shield. You should bond them to the shield at the point of penetration. In shielded rooms, this same advice applies to ventilation ducts, and pipes (water, sprinklers, gas, conduit, etc) Any conductive member crossing the shield must be bonded to it—no exceptions!

Fiber optics—This can be an effective way to make a nonconductive penetration in a shield. With the decreasing cost of fiber optics, you may want to consider this approach if you have a particularly vexing shield or cable-EMI problem.

Here are some other thoughts on shielding.

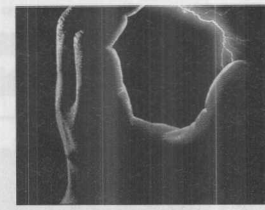
Grounding the shield—An earth ground plays no part in EMI-shielding effectiveness. A complete EMI shield forms a "Faraday cage," which protects the circuits inside the shield (or completely contains their fields) and does not require an earth connection. However, you may need to ground a shield for power safety purposes. If metal is exposed, it should be grounded through the green-wire safety ground to protect against accidental electrical shock.

Internal shields—Don't overlook using internal shields on critical circuits. Radio and television designers have been doing this for years, using selective internal shields on tuners, IF strips, power amplifiers, and the like. Digital designers are starting to apply this concept to high-speed systems and are enclosing microprocessors and crystals in small metal shields on the boards. If that's the only high speed part in your system, it makes sense.

Partial shields—While we emphasize full "Faraday-cage" shields, you may find partial shields that are as effective as internal shields. Putting a "fence" around critical circuits or adding a "cover" to a circuit can be effective in stopping near-field capacitive coupling. This concept was popular in vacuum tube days: it was very common to put a small shield between the grid and plate circuits to prevent unwanted feedback. Unlike the complete shields, these partial shields must be connected to signal ground to provide a return path for the current intercepted by the shield.

Keep cables away from slots and seams in shields—**Fig 10** illustrates the problem. Remember, those slots are little antennas, and they are "hot" with RF. We've seen this problem many times, and it's a sneaky shielding killer. Don't let careless cable routing catch you. EDN

That's it for our session on shielding. We've seen that most shielding design is not difficult, but it does require constant vigilance to maintain a shield's integrity. Thin materials work well for most high-frequency EMI applications, but slots and penetrations are big shielding killers. Low-frequency magnetic-field shielding is difficult to obtain and requires steel or other magnetic material to be effective. In the next chapter, we'll look at cables, or the "antenna farm", as we often refer to it in the EMI world.



The Designer's Guide to Electromagnetic Compatibility

Chapter 8

Cables and connectors... how to stop EMI leaks

For many designers, cables and connectors are an afterthought. After all, cables just connect things together. They are only a collection of passive wire and connectors—no special knowledge needed to understand a cable, right? Besides, most cable interfaces are slow. RS-232C at 9600 or 19,200 bps is hardly a high-frequency threat. And does anyone really care about 50- or 60-Hz from the power cables? If you share these beliefs, then you're setting yourself up for an EMI disaster.

Cables and connectors are major sources of EMI leaks into and out of all electronic systems. They act as antennas for radiated energy and as conduits for conducted energy. They not only carry intended energy, they can also carry a lot of unintended energy. That RS-232C data cable or 60-Hz power cord can pick up or radiate energy well into the GHz range. It can also carry spikes and other noise right to the heart of your system.

Often, cables often spell the difference between success and failure in the fight against EMI. One of the first things we do in troubleshooting a system is to examine the cables. We've seen numerous cases in FCC testing where wiggling an offending peripheral cable changed the emissions by 20 dB or more. We've seen other cases where moving an internal cable an inch or two changed ESD immunity by several thousand volts. We've solved many EMI problems just by changing the cable grounding. No doubt about it, cables and connectors are a leading cause of EMI problems.

In this chapter, we'll look at how to prevent and fix cable-related EMI problems. We'll examine cable construction, cable grounding and shielding, cable connectors, cable crosstalk, and cable routing. We'll show you how to design and treat your cables as the sophisticated systems they are, not just haphazard collections of wires and connectors.

Common vs differential mode

Before we go any further, we need to address a concept crucial to cables: common-mode EMI vs differential-mode EMI. Common mode refers to EMI currents that all flow in the same direction on a cable; differential mode refers to EMI currents that flow in both directions on the signal or power lines. **Fig 1** illustrates these modes. Note that common-mode currents return through the "ground" or some path other than the cable. Common mode is often referred to as "longitudinal" mode because the current flows along the cable. Differential mode is often referred to as "normal" mode because it flows in the direction of "normal" circuit currents.

Cables and connectors are major sources of EMI leaks into and out of all electronic systems.

Common-mode EMI currents on cables are a major cause of high-frequency failures for both emissions and immunity. Most FCC radiated-emission failures are caused by unintended common-mode currents flowing on a peripheral or power cable. Common-mode EMI currents are also a leading cause of low-frequency failures such as the unwanted hum in your stereo system. What makes common-mode currents so vexing is that they flow in "unintended" circuits, so they don't even show up on your schematics. But common-mode currents are real, and they cause very real EMI problems. It doesn't take much current to cause problems; even a few μA of common-mode current flowing on a 1 or 2m cable (antenna) can cause your system to fail an FCC test.

Differential-mode EMI currents on cables can also cause EMI problems. Crosstalk within a cable is a differential-mode problem. (However, cable-to-cable crosstalk can be either common mode or differential mode.) When dealing with EMI problems, you need to plan for both modes. A word of warning: if you only address one current mode, you've only addressed half of the problem.

Conversions between modes

One other key point needs to be made about mode conversions. All EMI currents begin or end at a circuit as differential-mode currents. Sometimes, there is a conversion from differential mode to common mode and vice versa. Often we can prevent an EMI problem by preventing these conversions from taking place.

Fig 2 shows two examples of differential-mode-to-common-mode conversion. At low frequencies, significant common-mode currents can result from

Divide and conquer—a cable-classification scheme

Several years ago, we were retained by a client to help with the design of a high-speed telecommunications switch. This system had cables that ranged in bandwidth from almost dc to over 100 MHz. This wide frequency range, coupled with conflicting beliefs, was causing a lot of confusion among the design team regarding the "best" cable approach for EMI control.

To sort out the confusion (and even settle some arguments), we came up with a simple cable-classification scheme that we have since used on other systems. The concept was to divide and conquer based on the bandwidth required by each type of interface. This scheme allowed tradeoffs between filters and shielding and provided easy guidelines for shielding, connectors, and grounding.

Table 1 illustrates the method we used. You can use this an example of "divide and conquer" in your cable designs.

Table 1—Cable/connector classifications

Class	Use	Bandwidth	Filter*	Shield/Connector	Ground
I	High-speed communications	>100 MHz	None	Very-high-quality coax (or fiber optics)	Both ends, no pigtails
II	LAN (Ethernet)	10 MHz	>10 MHz	High-quality coax	Both ends, no pigtails**
III	RS-232C (9600 baud)	10 kHz	>100 kHz	Medium-quality shielded cable/ metal connectors	Both ends, no pigtails
IV	Audio	3 kHz	<300 Hz >3 kHz	Shielded twisted pair	One end, pigtails OK
V	Power	60 Hz	>10 kHz	Twisted pair	N/A
VI	Alarm/indicators	<5Hz	>10 kHz	Twisted pair	N/A

* In this case, filter designs were based on bandwidth, size, and other system constraints.
** A hybrid ground (capacitor on one end, solid connection on the other) was used here to provide 60-Hz isolation against ground loops.
N/A=not applicable

ground loops. (We'll look at this subject in detail in a later chapter on grounding.) Noise currents in the ground can cause common-mode currents to flow over cables, as can magnetic-field coupling into loops formed by cables and the ground system. At high frequencies, common-mode currents can be caused by electromagnetic radiation or by ground currents inductively coupled to cables. Both cases are often caused by poor or improper cable grounding.

How cable shielding works

One of the reasons designers get confused about cables is that there are so many different opinions on cable shielding. Ask one expert, and he or she will recommend grounding cables at only one end. Ask another expert, and you'll be advised to use heavy braid and to ground both ends. Ask a third expert, and you'll be told to use steel or Mumetal and forget about grounding. And all three will be right, but only under the right circumstances!

Let's start with some basics. Cable shielding is similar to cabinet shielding. Both depend on intercepting electromagnetic energy and preventing it from entering or leaving the cable. Both use two mechanisms to provide shielding: reflection and absorption. Most cable shielding, however, depends on reflection; absorption makes almost no contribution. Absorption depends on skin depths, and you need material at least as thick as three skin depths to provide appreciable shielding. Most foils and braids are not thick enough (do not have enough skin depths) to provide absorption below 100 MHz. Two exceptions are low-frequency magnetic-field cable shields (they need to be thick and permeable) and solid conduits used at high frequencies.

You can even consider cable shields as an extension of the cabinet shield (**Fig 3**). This shielding model is often referred to as the "barbell" approach to shielding. As long as there are no breaks anywhere in the barbell, the shielding integrity of both the cabinets and the interconnecting cable is maintained.

There are some crucial differences between cable and cabinet shielding.

Fig 1—Common mode vs differential mode

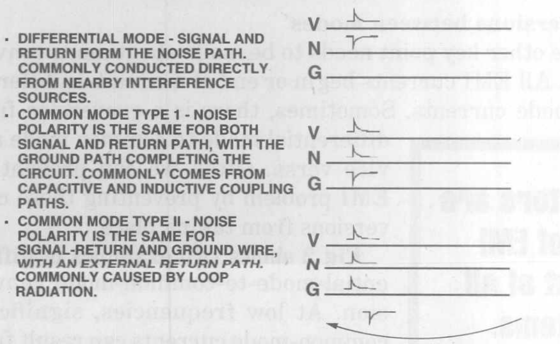
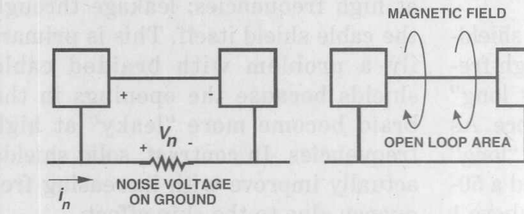
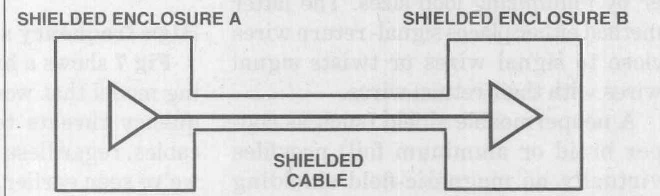


Fig 2—Common-mode to differential-mode conversion



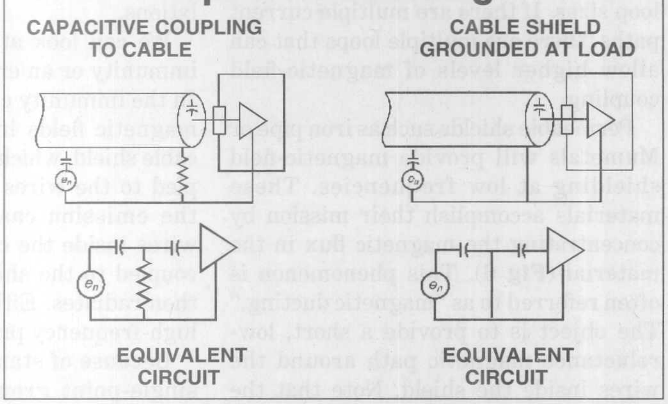
COUPLING PATHS ARE COMMON TO ALL WIRES IN THE CABLE.

Fig 3—Barbell approach in shielding



FULLY SHIELDED ENCLOSURES CONNECTED BY FULLY SHIELDED CABLE KEEP ALL INTERNAL CIRCUITS AND SIGNAL LINES INSIDE THE SHIELD.

Fig 4—Low-frequency capacitive shielding



Most cables are one dimensional (they have length), and most cabinets are three-dimensional (they have length, width, and height). Many cables use braid for shielding, and most cabinets have at least a uniform coating of solid metal. Most cables are subject to repeated mechanical stresses such as flexing, and most cabinets remain in fixed positions.

Three cable-shield types

It is customary to use three models to explain cable shielding. These models are analogous to the three different types of fields used to explain cabinet shielding. The three models provide insights on how, why, and when to use different shielding techniques and materials. They also explain why the same cable shields exhibit vast differences under various conditions.

The first two models (capacitive and inductive) explain the behavior of "electrically short" or low-frequency shields. These models work best on 60-Hz and audio-frequency problems. The third model (electromagnetic) explains the behavior of "electrically long" or high-frequency shields. This model works best on radio-frequency problems such as RF emissions or immunity.

The transition between "electrically short" and "electrically long" occurs at about ¹⁄₂₀ of a wavelength. For lengths shorter than this, you can model cables as lumped components. For lengths longer than this, include transmission-line effects in your modeling. **Fig 3** gives several examples of wavelengths and cable lengths vs frequency. *Note that at 1 MHz,* any cable 15m (about 50 ft) or longer is "electrically long," and at 10 MHz, any cable longer than 1.5m (about 5 ft) is "electrically long."

Thus, if your cables exceed a few feet and you are dealing with RF emissions or immunity above 10 MHz, use the "electrically long" or high-frequency-model design rules. Don't ever forget this vital piece of information if you design high-speed systems.

Fig 4 illustrates what is probably the easiest model to understand. This model works best for high-impedance circuits and low-frequency threats. A good example of this situation is 60-Hz capacitive coupling to high-impedance analog instrumentation electronics or telecommunications circuits.

If we go back to our "source-path-receptor" model for EMI, we see that we have undesired energy coupled to the receptor circuit through the electric field. You can model this coupling as a "mutual capacitance" between source and receptor. We can intercept this capacitive coupling by placing a shield between the two circuits and then connecting this shield to the victim-circuit's ground. This method diverts the undesired energy away from the receptor circuit.

For "electrically short" cables, the voltage potential is constant all along the shield. (At 60 Hz, a cable is "electrically short" for about 250 kilometers, or 150 miles!) Thus, only a single-point ground is needed for this low frequency. In fact, a single-point shield ground is preferred for low frequencies to prevent unwanted ground loops. However, the ground connection must provide a low-impedance path to its ground point. Up to about 10 kHz, a "pigtail" or length of wire can be used to provide this low-impedance connection. Above 10 kHz, however, pigtails become inductive and should not be used. (We like to limit pigtail shield grounding to 60-Hz problems.)

Low-frequency inductive shielding

Fig 5 shows the model that works best for low-impedance circuits and low-frequency threats. A good example of this is 60-Hz inductive coupling of interference to low-impedance control circuits. Typical low-impedance sources are high-current power lines and NMR (nuclear-magnetic-resonance) systems. Railroads and power companies often fight this interference battle, known as "inductive coordination."

In this case, a magnetic field couples the undesired energy into the receptor. You can model this coupling as a "mutual inductance" between the source and

receptor. You can intercept this inductive coupling with highly permeable shields or by minimizing loop sizes. The latter method either places signal-return wires close to signal wires or twists signal wires with their return wires.

A nonpermeable shield (such as copper braid or aluminum foil) provides virtually no magnetic-field shielding below about 1 kHz. In addition, single-point grounds (with or without a shield) are extremely important for low-frequency magnetic-field problems. A single-point ground ensures that currents flow in adjacent return wires to reduce loop sizes. If there are multiple current paths, there are multiple loops that can allow higher levels of magnetic-field coupling.

Permeable shields such as iron pipe or Mumetals will provide magnetic-field shielding at low frequencies. These materials accomplish their mission by concentrating the magnetic flux in the material (**Fig 6**). This phenomenon is often referred to as "magnetic ducting." The object is to provide a short, low-reluctance magnetic path around the wires inside the shield. Note that the smaller the shield's diameter, the shorter the path around the signal wires.

This situation results in an interesting phenomenon with permeable shields: the same material will work better with two smaller cables than with one large cable. This concept has helped bail us out of a couple of magnetic-field jams. However, a word of warning: group your signal or power lines with their returns in the same cable. If you group the returns in a separate cable, you will create an EMI monster.

High-frequency shielding

Fig 7 shows a high-frequency shielding model that works best for high-frequency threats to "electrically long" cables, regardless of the impedance. As we've seen earlier, a 5-ft cable is "long" at frequencies above 10 MHz, and a 50-ft cable is "long" at frequencies above 1 MHz. Thus, the high-frequency model is the one to use for RF emissions and immunity in the 30- to 1000-MHz range covered by FCC, VDE, and IEC regulations.

We can look at this model from an immunity or an emission point of view. In the immunity case, external electromagnetic fields induce current in the cable shield, which is inadvertently coupled to the wires inside the shield. In the emission case, energy from the wires inside the cable is inadvertently coupled to the shield's exterior, which then radiates. Either way, you've got a high-frequency problem.

Because of standing-wave effects, a single-point ground will not suffice. Even if we have a perfect 0Ω ground to infinitely high frequencies, if we move ¼ wavelength down the cable, we'll have a perfect "open" circuit. Thus, we must ground our cables at both ends for high frequencies, and the ground connections must provide low-impedance connections to the ground points. At 10 MHz and above, a low-impedance connection means full 360° circumferential bonds and metal connectors—no plastic connectors or pigtails allowed. Pigtails are entirely too inductive.

There is one more potential problem at high frequencies: leakage through the cable shield itself. This is primarily a problem with braided cable shields because the openings in the braid become more "leaky" at high frequencies. In contrast, solid shields actually improve with increasing frequency, due to the skin effect.

Cable researchers and manufacturers have come up with a useful parameter to measure this leakage effect, known as "cable transfer impedance." This test measures the longitudinal inside voltage caused by the current outside (or vice versa), and is expressed in Ω/m. The lower the number, the better the shield.

Fig 8 shows some typical cable-shield-transfer impedance values. Note that below about 10 MHz, there is little difference in shield performance, but above 10 MHz, there may be vast differences. **Fig 8** simply tells us that for RF threats below 10 MHz, just about any shield will work—provided it is properly grounded. At higher frequencies, it pays to spend the extra money for better shielding. The more coverage the better.

We've seen several clients burned by transfer impedance as they move higher in frequency. A classic example is using the same shielded cable on both a monochrome video cable (about 6-MHz bandwidth) and on a high-speed-graphics video cable (bandwidth of 50 MHz or more). We had one client who passed FCC emissions with the monochrome

Fig 5—Low-frequency inductive shielding

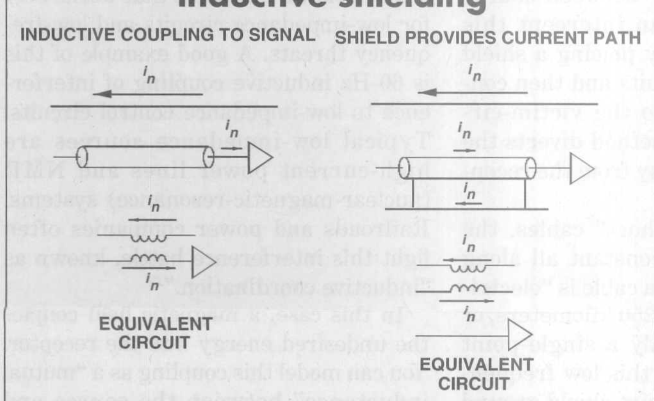
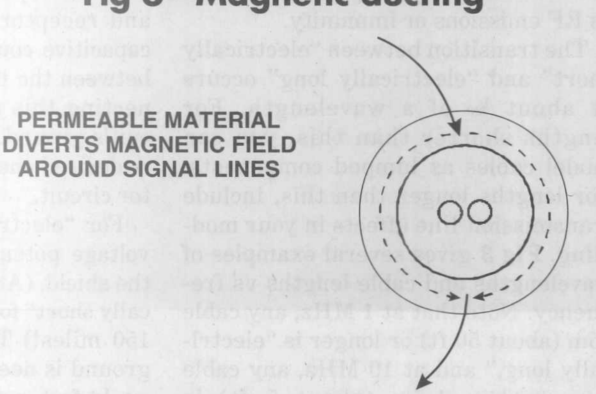


Fig 6—Magnetic ducting



monitor, but failed with a high-speed graphics monitor. Installing a "better" cable on the graphics monitor fixed the problem. (Even so, most cable failures are still caused by poor terminations and not by leakage through the shielding material. Be sure to check your connections before replacing the shield.)

A sure way to destroy cable shielding

With a reasonable amount of care, it's easy to provide enough cable-material shielding for even the most demanding requirements. It's also easy to lose virtually all the shielding effectiveness at the connectors. It's like a garden hose; you can have the finest hose money can buy, but if the connection to the faucet is bad, water sprays on everything. So it is with cables. If you have a poor connection at the connectors, you have RF everywhere.

We've already warned you about pigtails. You often see these on RS-232C cables where a drain wire passes through the connector on a pin. This scheme can totally destroy cable shielding above a few MHz. **Fig 9** shows the equivalent circuit for an inductive pigtail used as a shield termination. The LC combination forms a very efficient coupling network to your cable shield "antenna." In fact, that's the same configuration you'd see in a mobile-radio-transmitting antenna. Unfortunately, you don't want your shield to be an antenna.

Pigtails also form an unwanted entry point for ESD energy. Remember, ESD behaves like a VHF signal in the 100- to 300-MHz range, so pigtails are highly inductive with respect to ESD. We saw one case where reducing the pigtail length from a 4-in. wire to a ¼-in. strap raised the system's ESD immunity from 2000 to over 12,000V. If we could have eliminated the strap and gone to a full circumferential connection, we could have raised the system's ESD immunity even higher.

A quick recap of cable grounding

Questions about cable grounding are probably the most frequently asked EMI questions. So here is a quick summary:

(1) For low frequencies (under 1 MHz for cables up to 50 ft long), ground the cable shield at one end. This scheme avoids ground loops, which are primarily a low-frequency problem. Don't use pigtails for EMI above 10 kHz.

(2) For high frequencies (over 1 MHz for cables up to 50 ft long), ground the cable shield at both ends. Use full 360° circumferential bonds between the shield and connector and maintain metal-to-metal continuity between the connectors and the cabinet.

(3) Consider a hybrid ground (use a capacitor at one end) where high- and low-frequency problems can coexist. This problem is common for data-communications and LAN cables. Special connectors are available for this purpose. You can also make the capacitive connection yourself. (Keep the leads short.)

Design guidelines for cable shielding

Now that we've covered the theory and looked at the problems, let's discuss how to design and implement good shielded cables. As we did with cabinet shielding, most of our focus will be on RF shielding in the 30- to 1000-MHz range because that is where most of you will encounter problems. We'll also look at low-frequency shielding for designers who need to protect against 50- to 60-Hz threats.

(1) Determine your actual needs. As we've already seen, several factors affect cable shielding. The three key factors are *frequency range, cable length,* and *circuit impedances.* Let's take a brief look at these factors.

Frequency range: This is an obvious, but often overlooked, parameter for cable design. Do you need a high- or low-frequency shield? In many instrumentation or audio systems, the cable shield needs only to work at 60 Hz and nowhere else. For RF or ESD, the shield may need to work well at hundreds of MHz or beyond. As we've already seen, frequency has a major impact on cable and connector materials.

Cable length: The important parameter here is not absolute length but the wavelength of the highest frequency at which the shield must operate. Remember that cables are classified as "electrically short" if they are less than 1⁄20 of a wavelength at the highest frequency and "electrically long" if they exceed this length. As we've already seen, cable length has a major impact on where and how we ground cables.

Circuit impedance: Low impedances mean high currents that in turn create magnetic fields. High impedances mean low currents that in turn create electric fields. As we've already seen, circuit

Fig 7—High-frequency shielding

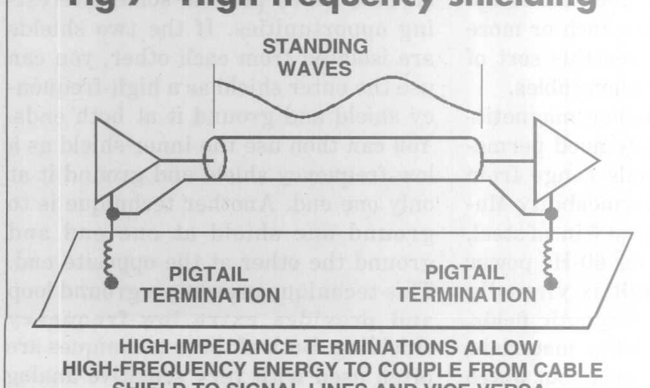


Fig 8—Transfer impedance

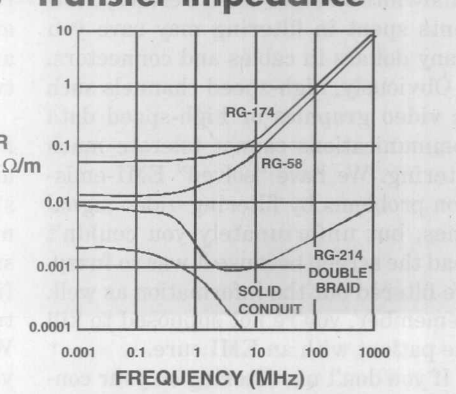
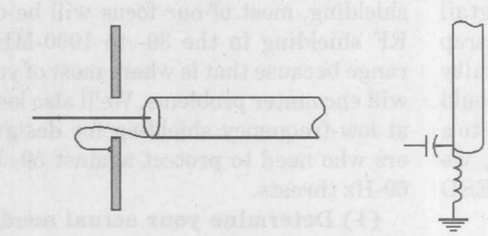


Fig 9—Pigtail-equivalent circuit



EQUIVALENT CIRCUIT

THE EQUIVALENT CIRCUIT OF A PIGTAIL TERMINATION CLOSELY RESEMBLES RADIO ANTENNA MOUNTING PRACTICES.

impedance has a major effect on the shielding material you need to use.

(2) Trade off shielding for filtering. You can alter your frequency needs by using filters. For example, many low-speed interfaces do not need wide bandwidth to function. Communication theory tells us that we only need a bandwidth equal to the data rate, but that limited bandwidth would give us sine waves instead of square waves. As a rule of thumb, we use 10× the data rate as an acceptable "cable bandwidth," which still leaves you with a decent-looking square wave while limiting the unnecessary high-frequency energy.

For example, a 19.2-kbps RS-232C channel only needs about 200 kHz of bandwidth so you can limit anything above 200 kHz with a lowpass filter. If you filter your signal lines, you can often greatly reduce, and in some cases even eliminate, data-cable shielding requirements. We do this to power lines because we really only need to pass 60 Hz.

We refer to this approach as "conservation of bandwidth." Good engineering suggests that we shouldn't use more bandwidth than we need. Besides, a few cents spent in filtering may save you many dollars in cables and connectors.

Obviously, high-speed channels such as video graphics or high-speed data communications cannot tolerate much filtering. We have "solved" EMI-emission problems by filtering video signal lines, but unfortunately you couldn't read the screen because it was so fuzzy. We filtered out the information as well. *Remember, you're not supposed to kill the patient with an EMI cure.*

If you don't use filtering on your connectors, then you must assume that the highest frequencies inside the unit will end up on the cable wires. Yes, those slow RS-232C cables, if unfiltered, can carry parasitic energy well into the GHz range. For emissions from unfiltered lines, we usually assume our cable-shield bandwidth is 20× the highest clock rate, just as we did for cabinet shielding. For immunity, you need to design for the highest required test frequency.

(3) Select the cable material. After you've determined your needs and decided on whether or not to use filters, you can select the cable-shielding materials. Here are some recommendations:

Low-frequency threats: Shielded twisted-pair wiring works very well for low-frequency threats. The shield protects against electric fields, and the twisted pairs protect against magnetic fields. If electric fields are not a concern, then simple twisted-pair wiring alone may be sufficient.

When using twisted pairs, the tighter the twist, the better the shielding and the higher the frequency. As a rule of thumb, we assume about 20 dB of attenuation when the twists are several turns per inch or more. Regular telephone wiring has about one twist per foot, which still works quite well for 60-Hz and audio-frequency rejection. "Data-grade" telephone wiring has about one twist per inch, which is needed to control crosstalk at higher data rates. For data in the 100-kHz range and higher, 10 turns per inch or more are typical. You often see this sort of twist in twisted-pair ribbon cables.

For large, low-frequency magnetic-field threats, you'll likely need permeable shielding. Materials range from steel conduit to high-permeability Mu-metals. You'll need at least ⅛ in. of steel, such as rigid conduit, for 60-Hz power fields. Thinwall conduit is virtually transparent to 60-Hz magnetic fields. With the high-permeability materials, you can use thinner material, but watch out for saturation. Remember to minimize the shield's circumference; your goal is a short magnetic-field path. Also, remember that two smaller shielded cables will work better than one big one.

High-frequency threats: If you can't filter your data lines, then you'll most likely need shielding for RF emissions and immunity in the 30- to 1000-MHz range. You also need metal-to-metal connections, and metal or metallized backshells. The cable shield must mate with the backshell through a 360° metallic bond.

For frequencies below 10 MHz, just about any shield braid will work. At frequencies above 10 MHz, it pays to buy better shielding with a lower transfer impedance. Vendors often refer to the "optical coverage" of their braids. At 10 MHz and above, we recommend 95% coverage or higher. The tighter the braid, the higher the coverage (and the expense).

We are often asked about solid- or Mylar-foil shielding. Theoretically, this type of shield should perform much better than braid because there are no holes in the foil. However, there are several potential problems. First, the shield seam must be very tight, or it will leak. Second, the foil can split open under mechanical stress, and the split will allow large amounts of leakage. Third, spiral-wrapped foils may introduce unwanted inductive effects. We prefer to see foils combined with an outer braid. That way, if the foil opens up, you still have the braid to provide electrical continuity. The combined foil-braid shields provide some very good long-term shielding.

We are also asked about double shields, which provide some interesting opportunities. If the two shields are isolated from each other, you can use the outer shield as a high-frequency shield and ground it at both ends. You can then use the inner shield as a low-frequency shield and ground it at only one end. Another technique is to ground one shield at one end and ground the other at the opposite end. This technique prevents a ground loop and provides extra low-frequency shielding. Both of these techniques are often used with very sensitive analog instrumentation. If your concerns are

solely high frequencies, you can ground both shields at both ends and gain from the additional coverage. This is the idea behind double-shielded coaxial cables.

(4) Choose the connectors. The important parameter for cable connectors is frequency. The higher the frequency, the better the connector must be. Your shielded cable can be no better than the connector; even the best of cable shields will leak with poor connectors.

For low-frequency shielded cables (dc to 10 kHz), simple plastic connectors with drain wires work quite well, which is why these connectors are popular for telephone cables, instrumentation cables, and low-speed data-communications cables.

For medium-frequency shielded cables (10 kHz to 10 MHz), metal or metallized-plastic connectors work well, particularly if they provide a circumferential grip on the cable shield. The connectors should also provide a metal-to-metal connection between the connector shells.

For high-frequency shielded cables (10 to 1000 MHz), we recommend high-quality metal connectors used with high-quality shielding. You may also need RF gasketing at the various joints to maintain a high-frequency seal.

Don't overlook filtered connectors, particularly for low-speed data lines such as RS-232C. Many designers reject filtered connectors because they cost quite a bit more than nonfiltered connectors. However, filtered connectors offer several potential advantages. They may let you use much cheaper cables. They don't take up any space on your circuit board. They are also a good investment if you are concerned about electrostatic discharge. Even if you don't have a mandated ESD requirement, connector pins are very likely ESD targets in the real world, and it pays to protect your I/O pins with filters.

(5) Pay attention to all the joints. This is an extremely critical problem area for shielded cables. Joints are the main reason why shielded cables fail. We've seen this problem dozens of times in both compliance testing and in EMI-induced field failures.

Cables and connectors have several weak points (**Fig 10**). You can have leakage at the cable-connector junction, the connector-connector junction, and the connector-chassis junction. Even the connector shell itself can leak if the two halves don't mate well. (Such leakage usually isn't a problem for commercial designs below about 300 MHz, but military designers worry about this problem. As system speeds increase, however, leakage is becoming an increasing concern for all systems.) Remember our garden hose analogy: keep everything RF tight.

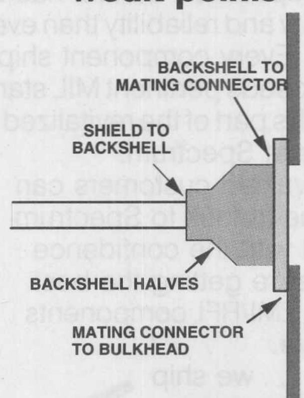
Cable to connector: As we've already stressed, you need a full circumferential bond between the shield and connector for high frequencies. Bonding techniques range from simple gripping mechanisms to special clamps or even soldering in extreme cases.

Connector to connector: At a minimum, you want to maintain metal-to-metal contact through the connector shells. Schemes range from smooth-sliding metal contacts to "dimples" or fingerstock. Incidentally, we've found that data cables with "dimpled" connector shells outperform smooth connector shells above 500 MHz, proving once again that clever engineering pays off.

Connector to chassis: Don't lose your shielding here. One problem we often see is chassis connectors that do not always overlap the connector cutouts. The imprecise fit creates a slot between the connector and the cabinet. This slot is double trouble because it not only destroys the shield impedance, but also couples RF onto the cable shield through the slot leakage. If you can't use "fat" connectors to cover the openings, several vendors make special RF gaskets to seal these unwanted leaks.

(6) Pay attention to cable routing. This final bit of advice is aimed at system designers, because most equipment designers have little control over how external cables will be routed.

Fig 10—Connector weak points



Equipment designers may want to read on, however, because you will probably be blamed for cable routing problems anyway.

The secret is simple: keep "noisy" cables away from "sensitive" cables. Noisy cables include input-power wires, motor or relay control wiring, and RF-transmitter coaxial transmission lines. Sensitive cables include analog or digital signal cables, telephone wiring, and local-area-network cables.

We like to maintain at least 12 in. of separation between noisy and sensitive cables. Whatever you do, don't lash all the cables together with cable ties just to make everything neat. We've seen too many cases where spikes from power wiring jammed adjacent digital cables or hum upset adjacent analog cables. We've also seen several cases where a high-power-RF transmission line was the culprit. In one case, our client argued that the RF wire couldn't be the problem because he had learned in school that no electromagnetic field exists outside a coaxial cable. Well, real coax cables do leak, and this characteristic becomes significant at high power levels. Moving the adjacent RS-232C cable solved the problem. EDN

That's it for our session on the care and feeding of cables and connectors. We've seen that cables are actually sophisticated systems that deserve sophisticated engineering attention. If you don't give them the attention they require, we can almost guarantee you will encounter EMI problems. In the next chapter, we'll look at power supplies, another key candidate for EMI design.

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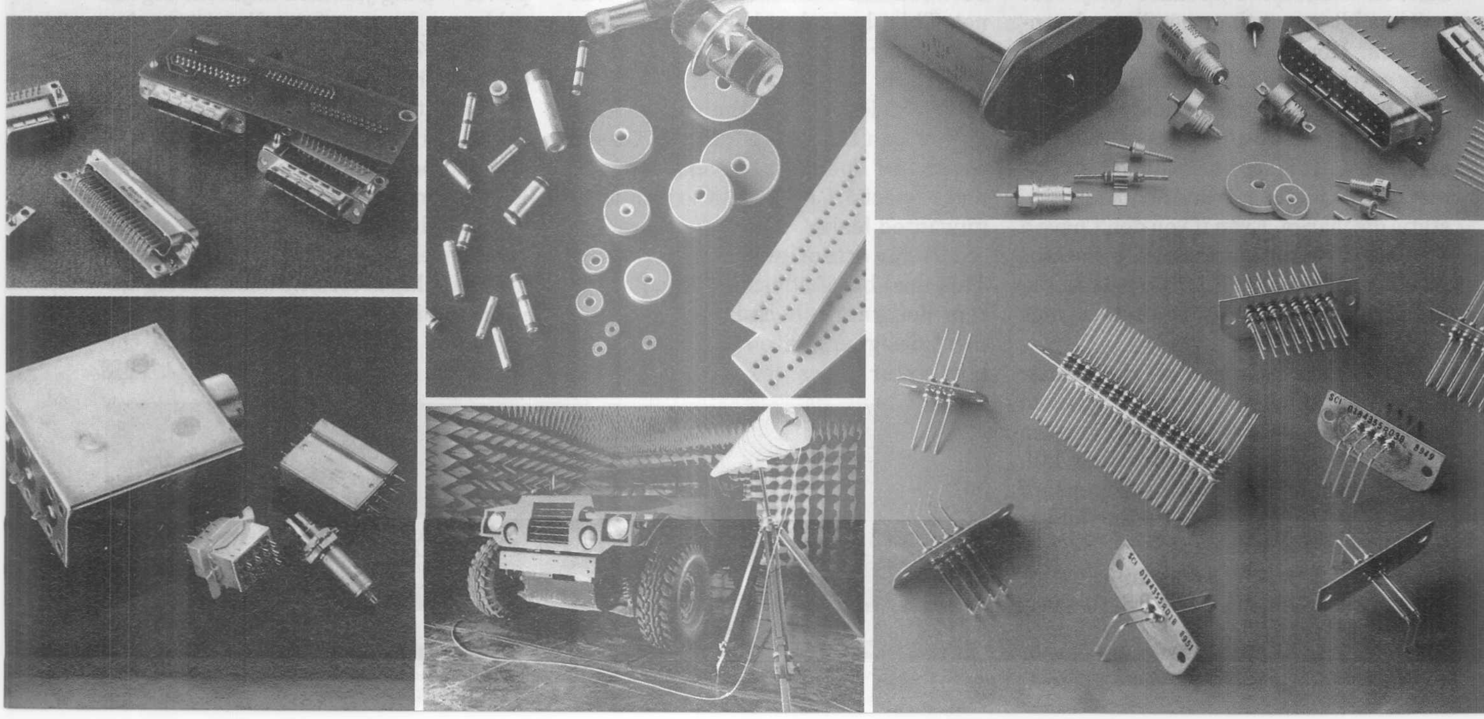
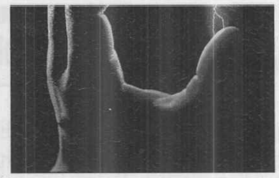




Power-supply design for EMI... filters aren't enough

Behold the lowly power supply. It labors along in its mundane task of changing ac into dc (or dc into dc, and even dc into ac), shifting voltages to more useful levels, and even providing voltage regulation and current limiting. It takes all kinds of abuse from the outside world such as spikes, notches, sags, surges, and maybe even lightning transients. It gets blamed for consuming too much power and more recently for creating harmonic currents that burn up transformers and neutral wires. (We wonder if power supplies aren't just settling some old scores for all the noise they've had to swallow in the past.)

Power supplies are often not appreciated or are misunderstood. Yet they are necessary in almost every system. They are key sources and receptors of both conducted and radiated EMI. Sometimes power supplies are even unwitting coupling paths for EMI that blasts right through the supply and into the system's guts. When these events happen, problems are bound to occur because every circuit in a system is ultimately connected to a power supply.

In this chapter, we'll look at the special EMI problems associated with power supplies, and we'll give you some EMI guidelines to prevent or solve those problems. We'll also give you some quick-and-dirty design guidance for power filters and transient protection that can help even if you always buy power supplies off the shelf.

Incidentally, this chapter is not aimed at the experienced power supply designer—most experts are well aware of these problems. Rather, we aimed this chapter at the nonexpert who may be called upon to select or even design a power supply for the first time. Our objective is not to make you a power-supply expert (that could takes years of practice), but to help identify and prevent some of the more common EMI problems you'll likely see with your power supplies.

Power supplies: sophisticated systems

Once upon a time, power supplies were simple. They used simple devices such as diodes, transformers, capacitors, and inductors to do their job. More advanced designs used an active regulator such as a mercury-vapor rectifier (with its beautiful purple glow) to hold the output voltage relatively constant. Overcurrent protection consisted of fuses—none of this fancy current-limiting stuff back then.

Back then, most electronics consisted of vacuum tubes, so issues such as voltage regulation and high efficiency were not as important as today. Most power supplies were linear and efficiencies were often well under 50%. Because of their large transformers and rugged vacuum-tube rectifiers (recall the old 5U4), power supplies usually ignored spikes and other transients. About the biggest EMI problem back then was open filter capacitors, which caused an annoying hum in audio circuits from the 60-Hz ripple on the B+ voltage to the tubes.

All this changed with the semiconductor revolution. Transistorized circuits, and later integrated circuits, operated at much lower voltages and demanded much better regulation. Furthermore, these systems required higher efficiencies. It didn't make much sense to save all kinds of power with transistors or ICs only to waste it on inefficient power supplies. Besides, the low costs of solid-state devices made sophisticated power control much more practical.

Today's power supplies are highly sophisticated power-conversion systems. Thanks to switching-mode designs, efficiencies often exceed 90%, and the sizes of the supplies are mere fractions of their vacuum-tube predecessors. Active devices provide feedback, stabilized regulation, and almost instantaneous overcurrent protection. Inexpensive ICs provide additional local voltage regulation at low cost. New devices on the market even provide power-factor correction on a cycle-by-cycle basis to limit harmonic distortion.

All this sophistication, however, comes at a price. Modern power supplies are robust sources of both conducted and radiated EMI. After all, a switched-mode power supply is really just a high-power oscillator (from an EMI standpoint) and is rich with switching harmonics. Direct rectification of the ac line adds to the fun, hacking up sinusoidal waveforms and creating all kinds of 50- or 60-Hz harmonics. Power sup-

Once upon a time, power supplies were simple.

plies can be victims of EMI, too. The sensitive electronic circuits used to provide feedback and regulation are often upset by RF energy, transients, or even internal system noise. Any power-supply design must consider EMI from the start.

Power supplies as sources of EMI

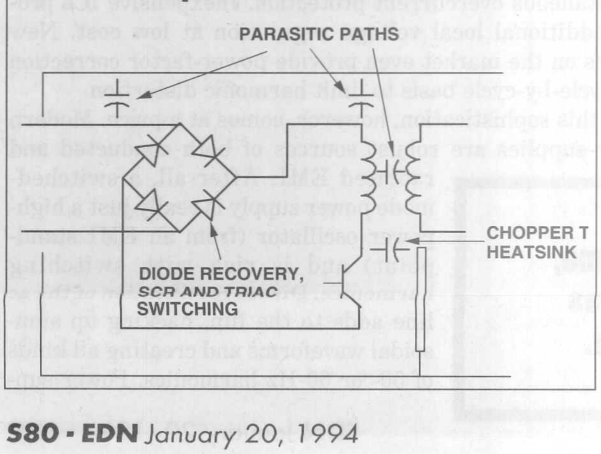
Power supplies have multiple EMI sources. **Fig 1** highlights several potential EMI problems originating from within a supply. Some of these are active, such as switching oscillators or switching voltage regulators; others are passive, such as rectifiers. Some represent intended circuits; others are unintended circuits (remember our "hidden schematic" concept). Some power supplies generate differential-mode EMI, and others cause common-mode EMI (see **Fig 2** for a quick review of these two important modes). Some power supplies are high frequency and some are low frequency; the situation can become quite complicated. Let's take a look at two key emissions problems: switching and power harmonics.

Switching harmonics are the most obvious switching-mode power-supply EMI issue. After all, switching-mode circuits use a high-current, high-speed oscillator that is rich with harmonics thanks to its square waveform. Unlike digital clocks, you don't want to slow the edges of a switched-mode power supply, because that would reduce efficiency and dump energy into the switch. Most switching-mode power-supply problems occur in the 10-kHz to 10-MHz range, although we've seen some high-speed switchers cause EMI problems at frequencies over 100 MHz.

These switching harmonics can cause serious conducted emission problems. Most switchers today operate in the 10- to 100-kHz range. Because of their square edges, the harmonics generated by switching-supply waveforms decrease slowly at 20 dB/decade. These harmonics often cause conducted emissions to exceed FCC Part 15 conducted limits in the 450-kHz to 30-MHz range. It's even worse with the German VDE conducted limits, which begin at much lower frequencies—150 kHz for Class A (commercial) and 10 kHz for Class B (residential) electronics. Use input-power filters to contain these conducted emissions but remember, the lower the frequency, the bigger the filter.

Switching harmonics can also cause low-frequency radiated emission problems. For example, both the military (MIL-STD-461) and Germany (VDE) test for low-frequency magnetic-field emissions in the 10-kHz to 30-MHz range. Because power supplies use high currents, they are ready sources of magnetic fields. Magnetic-field shielding and careful attention to circuit layout can control these radiated emissions. As we saw in an earlier article, low-frequency magnetic-field shielding can be difficult. You'll probably need steel or perhaps even high-permeability mu-metal to be effective. Circuit layout can pay big dividends here by minimizing the radiated emissions at the source.

Fig 1—Power-supply EMI problem areas



Switching harmonics usually do not cause high-frequency radiated emission problems. Most commercial standards (FCC, VDE, CISPR) only test for electric-field radiated emissions between 30 and 1000 MHz. At these higher frequencies, switching harmonics are usually well below the limits. However, they may cause interference problems with AM and short-wave-radio reception (550 kHz to 30 MHz), or even television reception in fringe or low-signal areas. Existing FCC limits are based on protecting televisions against interference in a strong-signal urban setting and do not cover all interference possibilities. At low signal levels, low levels of outside interference can severely degrade the signal-to-noise (S/N) ratio. The solution to this problem is increased shielding and filtering to reduce EMI levels. Remember, meeting an EMI standard does not guarantee you'll never have EMI problems!

Switching harmonics can also cause internal equipment problems. The most obvious problem is output-voltage ripple. This is usually not a problem with digital circuits, but it may cause problems with sensitive analog circuits. For this reason, many designers insist on linear supplies for analog circuits, because they usually have much less output ripple. An alternate solution is to provide additional voltage regulation for the analog loads.

We've also seen internal equipment problems with CRT displays and magnetic storage devices such as hard drives. These problems are usually caused by electric- or magnetic-field coupling into low-level analog circuits. (Digital signals are usually not affected by this problem.) A helpful hint—electric fields are more likely to affect high-impedance circuits; magnetic fields are more likely to affect low-impedance circuits. Both types of fields are present near power supplies. Solutions to such interference problems include electric-field shielding (using aluminum or copper), magnetic-field shielding (using steel or mu-metal), and simple separation of the circuits and careful routing of traces and cables.

Power-frequency harmonics as a problem is a bit more subtle than EMI from switching circuits, and it has been gaining increased attention of late. This problem is often referred to as harmonic distortion, and in severe cases, power-frequency harmonics can overheat external wiring and transformers. Most of the heating problems are caused by the first twenty harmonics of the power frequency, up to about 1.0 kHz for 50-Hz power-line frequencies,

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UWR-3.3/1800-D5	3.3	1800	4.7 - 7	50	70%	500	2 x 1 x 0.375	$60
UWR-3.3/2500-D12	3.3	2500	9 - 18	50	75%	500	2 x 1 x 0.375	$60
UWR-3.3/1800-D48	3.3	1800	18 - 72	50	73%	500	2 x 1 x 0.375	$60
UWR-3.3/4250-D5	3.3	4250	4.6 - 13	75	73%	500	2 x 2 x 0.45	$68
UWR-3.3/4850-D12	3.3	4850	9 - 36	75	75%	500	2 x 2 x 0.45	$68
UWR-3.3/4850-D48	3.3	4850	18 - 72	95	78%	500	2 x 2 x 0.45	$68
UNR-3.3/7500-D5	3.3	7500	4.5 - 5.5	75	90%	None	2 x 1 x 0.375	$39
UNR-3.3/15000-D5	3.3	15000	4.5 - 5.5	100	85%	None	2 x 2 x 0.45	$44
UNR-2.1/8000-D5	2.1	8000	4.5 - 5.5	75	80%	None	2 x 1 x 0.375	$39
UNR-2.1/16000-D5	2.1	16000	4.5 - 5.5	100	79%	None	2 x 2 x 0.45	$44

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to 1.2 kHz for 60-Hz power, and 8 kHz for 400-Hz power systems. However, we have seen "high-frequency noise" problems from these harmonics as high as a 100 MHz, showing up as radio and television interference.

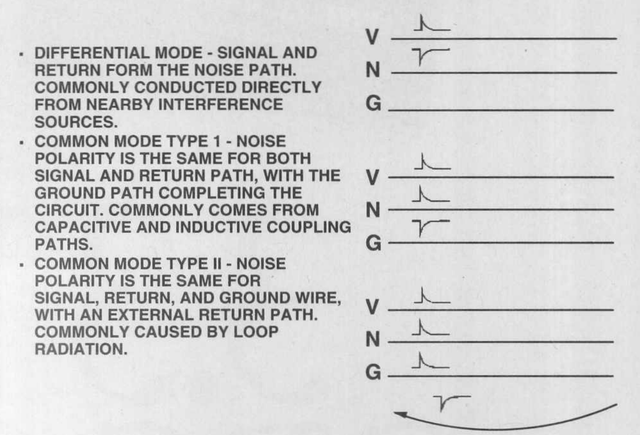
Although it's more of a system problem than an equipment problem, equipment-level regulations are starting to include limits on harmonic distortion. The most prominent of these regulations is IEC 555-2, which will affect equipment sales to European Market customers. This regulation's objective is to limit the total harmonic distortion at the power input on each piece of equipment. We take a different approach in the US, where the power utility effectively limits the harmonics at the power service entrance to a building. While this approach helps the power utility, it does nothing to protect the internal building wiring.

Switching power supplies aggravate harmonic-distortion problems through direct rectification of the power mains and storage of the rectified energy directly into a "bulk dc" capacitor. This form of power conversion creates current spikes at the peak of the voltage cycle as the bulk capacitor is recharged. The current is not drawn over the entire cycle, as is the case with a linear load. Linear supplies create much less of a problem because there is usually an intervening transformer—or better yet, a choke-input filter—that smoothes current spikes. Incidentally, this problem is often erroneously blamed on switch-mode power supplies. It is not the switcher that causes the problem—it's the direct rectification of the power line without the benefit of any intervening inductance that's the culprit.

In addition to current distortion, the voltage waveform can also become distorted. Voltage distortion is caused by the source impedance and Ohm's law. With a perfect 0Ω power-line source, current distortion wouldn't cause voltage distortion. Therefore, the lower the source impedance, the lower the voltage distortion. This is why switchers like to see a low dynamic power-line source impedance. If the source impedance is high, as it is in some types of voltage regulators and inverters, the switcher and the regulator may fight each other, resulting in poor system operation.

Another helpful hint: most harmonic-distortion specifications limit distortion to 5% or less. If you look at the voltage or current waveform with an oscilloscope, you will detect distortion visually at about 2%. If the waveforms look like pure sine waves, your signals are probably pretty clean. If the waveforms appear distorted, you may have harmonic problems.

Fig 2—Common mode vs differential mode



There are several solutions to these distortion problems. As mentioned earlier, input transformers or choke-input filters may help. There are now several power-factor-correction ICs that may help by spreading current pulses over the entire power-line cycle. For high-frequency noise problems, EMI filters are the solution.

Power supplies as victims of EMI

Because power supplies are connected to the outside world through the power mains, they are subjected to a wide range of power perturbations, ranging from lightning spikes to power brownouts. We looked at many of these in the previous chapter on power disturbances.

These disturbances can cause direct problems with the power supply, or they can cause indirect problems by using the power supply as a path to your system's internal electronics. The latter case is particularly prevalent at higher frequencies or with fast spikes.

Direct effects on power supplies: The most obvious causes of direct power-line problems are large spikes, large notches, and large over/under voltages. The very high energy levels in large spikes and overvoltages can cause damage; large notches and undervoltages can cause upsets through energy starvation.

Low-level transients can also cause direct problems with power supplies. In most cases, these transients result in erratic operation rather than damage. Low-level transients include high-speed transients such as EFT (electrically fast transients), motor/switching transients, or even ESD (electrostatic discharge) to input power and ground terminals.

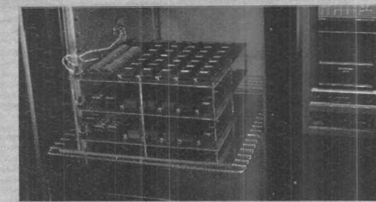
Analog disturbances can also cause direct problems that result in erratic operation. For example, voltage regulators are often upset by high levels of radio-frequency energy that saturate low-level regulator circuits. The switching circuits can be upset by high levels of audio frequency, particularly if the audio frequency matches the switching frequency. Sensitive internal electronics can even be upset by slow sags and surges that can slowly "modulate" sensitive electronics. This problem is particularly vexing if the modulation occurs within a feedback loop in the power supply.

Indirect effects on power supplies: Sometimes the power supply is not the main culprit, but rather an accomplice to an EMI problem. EMI problems often occur at high frequencies, where common sense says they should not be a problem. Unfortunately, the concept of the hidden schematic applies to power supplies as well as other circuits.

Very fast transients (such as EFT or

Emissions and Immunity Testing

Photo courtesy of EMCO



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ESD) often pass right through a power supply and wreak havoc on internal circuits. At first glance, this seems impossible given all the internal filtering in a power supply. But these internal filters are designed to filter ripple at relatively low frequencies and are often very ineffective above a few MHz. Even RFI filters on the input power lines may not be effective above 30 MHz, the upper limit for FCC/VDE conducted-emissions tests.

EFTs have significant energy beyond 50 MHz, and ESD transients have energy well into the 100- to 300-MHz range. Internally generated EMI such as clock transients can also have energy well into the hundreds of MHz. Unless you provide high-frequency filtering in the power supply, this high-frequency energy can simply blast right through in either direction.

How much power supply protection is needed? Unless the design parameters are already specified, we use the "power-line voltage-susceptibility curve" described in the new IEEE Std 1100-1992 (IEEE Recommended Practice for Powering and Grounding Sensitive Electronic Equipment). This curve says that your power supply should be able to withstand a long-term 106% overvoltage and 87% undervoltage. It should be able to withstand a 300%, 100-μsec transient; a 200%, 1-msec transient; etc. Your power supply should also be able to withstand a total loss of ½ cycle (8.33 msec for 60 Hz) of power.

If lightning transients are a concern, we also use IEEE C62.41 (IEEE Recommended Practice on Surge Voltages in Low-Voltage AC Power Circuits). Our recommendations are summarized in the **box**, "Developing a power spec" which appears in Chapter 5.

Guidelines for power-supply design

Now let's look at some measures to prevent or solve power-supply EMI problems. It's not enough to add just a filter or transient protector—you must properly design and install these protection circuits to realize their full benefits. Furthermore, clever electrical and mechanical design can prevent many EMI problems from occurring in the first place.

Block conducted and radiated noise

When most of us have a power-line EMI problem, we reach for the filter catalog. But unless you select the right filter and install it correctly, you may not solve the problem. In fact, the filter may even make matters worse; they can't solve all your problems. Nevertheless, filters are a prime weapon in the battle against power-line EMI, so here are some guidelines on using EMI power filters. (If you want to design your own filter, see **box**, "Quick-and-dirty EMI power-filter design.")

First, determine your needs by asking some key questions about the application:

(a) What are your voltage and current requirements? The higher the current, the larger the filter's inductors need to be to prevent saturation. This requirement results in a physically larger filter.

(b) What are your frequency requirements? Most commercial filters are specified from 10 kHz to 30 MHz, and military filters are rated from 10 kHz to 1 GHz. For commercial designs meeting FCC limits, the filter should provide attenuation from 450 kHz to 30 MHz (or higher). For VDE limits, the lower end goes to 150 kHz for Class A and down to 10 kHz for Class B. As we'll see later in this chapter, the 30-MHz upper limit for commercial filters may not be good enough, and additional protection may be necessary.

Quick-and-dirty EMI power-filter design

Even though most of us buy EMI power filters off the shelf, there are times when you may want to build your own. Here are some guidelines we've picked up over the years from some experienced power-filter designers. (Thanks to our friends Russell Pepe of Schaffner and Bill Parker of Parker Engineering.)

First, separate the filter into differential-mode and common-mode components. We've already seen that both modes are present and a power filter must be designed to attenuate both modes. Differential-mode noise dominates at frequencies below 1 MHz; common-mode noise dominates at frequencies above 1 MHz. Furthermore, differential-mode noise tends to be inductive, so the differential (line-to-line) capacitors should face the noise source. Common-mode noise tends to be capacitive, so the common mode inductors should also face the noise source. Remember, we're looking for the maximum mismatch in impedance.

Here are some comments on the individual filter components for use in switch mode power supplies:

Differential-mode capacitors: Use capacitors with high surge-voltage ratings (1200V or more). Size capacitors so the capacitive reactance (X_c) is less than 1% of the load impedance at 60 Hz. For small filters, typical values are in the 0.1- to 2.2-μF range.

Differential-mode inductors: Use molyperm or powdered-iron cores with a low permeability in the 60 to 120 range. Size chokes so the inductive reactance (X_l) is greater than 10× the load impedance at 60 Hz. For small filters, typical values are in the 100- to 200-μH range.

Common-mode capacitors: Use high-frequency capacitors and as much capacitance as the leakage limits allow. Typical values are 2200 to 4700 pF for commercial applications. (Medical filters generally allow no common-mode capacitors because of the very low leakage current limits.)

Common-mode inductors: Use high-permeability ferrite cores, with as much inductance as you need to work with the common-mode capacitors. Typical values for small supplies are 5 to 10mH. If you need more than 10 mH, add two inductors in series to keep the inductor's self-resonant frequency high.

How much attenuation do you need? Aim for a 3-dB margin below 250 kHz, a 6-dB margin between 250 kHz and 1 MHz, and a 10-dB margin above 1 MHz.

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Unipolar Models	V_{IN} Range (Volts)	V_{OUT} (Volts)	I_{OUT} (mA)	R/N (mV, p-p)	Efficiency (Min.)	Case	Price (100's)
UWR-3.3/4850-D12	9 - 36	3.3	4850	75	74%	C4	$76
UWR-5/4000-D12	9 - 36	5	4000	100	80%	C4	$76
UWR-12/1650-D12	9 - 36	12	1650	100	81%	C4	$76
UWR-15/1300-D12	9 - 36	15	1300	100	82%	C4	$76
UWR-5/500-D48	18 - 72	5	500	120	75%	C1	$45
UWR-12/250-D48	18 - 72	12	250	150	76%	C1	$45
UWR-15/200-D48	18 - 72	15	200	150	76%	C1	$45
UWR-3.3/1800-D48	18 - 72	3.3	1800	75	72%	C2	$66
UWR-5/1800-D48	18 - 72	5	1800	75	77%	C2	$66
UWR-12/750-D48	18 - 72	12	750	75	80%	C2	$66
UWR-15/600-D48	18 - 72	15	600	75	80%	C2	$66
UWR-3.3/4850-D48	18 - 72	3.3	4850	100	78%	C4	$76
UWR-5/4000-D48	18 - 72	5	4000	100	80%	C4	$76
UWR-12/1650-D48	18 - 72	12	1650	100	81%	C4	$76
UWR-15/1300-D48	18 - 72	15	1300	100	82%	C4	$76

Case Dimensions: C1 - 1.25" L x 0.80" W x 0.43" H C2 - 2.00" L x 1.00" W x 0.375" H C4 - 2.00" L x 2.00" W x 0.45" H

Bipolar Models	V_{IN} Range (Volts)	V_{OUT} (Volts)	I_{OUT} (mA)	R/N (mV, p-p)	Efficiency (Min.)	Case	Price (100's)
BWR-5/1700-D12	9 - 36	±5	±1700	100	82%	C4	$76
BWR-12/830-D12	9 - 36	±12	± 830	100	81%	C4	$76
BWR-15/670-D12	9 - 36	±15	± 670	100	81%	C4	$76
BWR-5/250-D48	18 - 72	±5	± 250	120	73%	C1	$45
BWR-12/125-D48	18 - 72	±12	± 125	150	80%	C1	$45
BWR-15/100-D48	18 - 72	±15	± 100	150	80%	C1	$45
BWR-5/700-D48	18 - 72	±5	± 700	100	76%	C2	$66
BWR-12/415-D48	18 - 72	±12	± 415	75	79%	C2	$66
BWR-15/330-D48	18 - 72	±15	± 330	75	79%	C2	$66
BWR-5/1700-D48	18 - 72	±5	±1700	100	81%	C4	$76
BWR-12/830-D48	18 - 72	±12	± 830	85	81%	C4	$76
BWR-15/670-D48	18 - 72	±15	± 670	85	82%	C4	$76
Triple Models							
TWR-5/1200-12/250-D48	18 - 72	5/±12	1200/250	75/175	81%	C4	$76
TWR-5/1500-12/250-D48	18 - 72	5/±12	1500/250	75/175	79%	C4	$76
TWR-5/1800-12/200-D48	18 - 72	5/±12	1800/200	75/175	81%	C4	$76
TWR-5/1000-15/250-D48	18 - 72	5/±15	1000/250	75/175	79%	C4	$76
TWR-5/1500-15/250-D48	18 - 72	5/±15	1500/250	75/175	81%	C4	$76
TWR-5/1800-15/150-D48	18 - 72	5/±15	1800/150	75/175	80%	C4	$76

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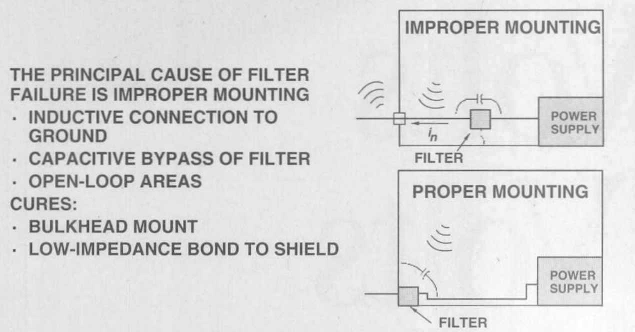


Fig 3—Filter mounting and grounding

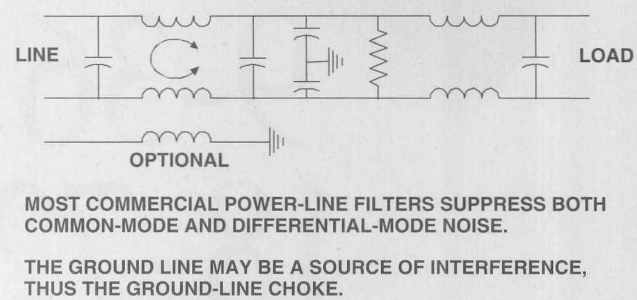


Fig 4—Typical EMI filter

(c) How much attenuation do you need? If you have failed an EMC test, you'll know the exact amount needed and at what frequency. Otherwise, for commercial designs we like to see at least 30 dB of attenuation for Class A devices and 40 dB for Class B devices, to at least 30 MHz. For military designs, we like to see at least 40 to 60 dB of attenuation from 10 kHz to 1 GHz.

(d) What safety-agency approvals do you need? You need UL for the United States, CSA for Canada, VDE/TUV/CE for Europe, etc. These requirements are mandatory.

(e) What are your leakage current limits? Incidentally, this is not a measure of "quality." Leakage current is determined by line-to-ground (common-mode) capacitance. These levels are typically limited by safety agencies to the range of 500 μA to 5 mA, which in turn limits the values of the common-mode capacitors. Some medical devices must limit leakage currents to 10 μA, which all but preclude common-mode capacitors.

Next, make sure you properly install the filter. There are two key issues: filter grounding and high-frequency coupling around the filter (**Fig 3**). Here are three filter-installation hints:

(a) Always make sure that the filter's metal case makes a direct, low-impedance contact to the metal cabinet or circuit-board ground. Never ground a filter through a wire, however short. A wire is much too inductive.

(b) Always mount the filter as close to the cabinet entry point as possible. The best installation is bulkhead mounting right at the cabinet, which also helps maintain shielding integrity. As you go higher in frequency, the filter and the shield become partners in blocking EMI.

(c) Never route the filter input leads adjacent to the output power leads. It is also prudent to keep the filter input leads away from any signal leads or cables.

Finally, be sure to provide both common-mode and differential-mode protection. Most commercial EMI filters provide protection against both coupling modes. **Fig 4** shows a typical EMI filter configuration with protection for both modes. If you only filter one mode, you are only doing half the job. Both modes exist in the real world.

High-frequency power-line protection

As we've already seen, most commercial filters are only rated to 30 MHz, which is a result of two factors. First, commercial conducted limits only go to 30 MHz. Second, in the past, most power lines did not contribute to radiated problems. (In the good old days of 4-MHz μPs, the internal power-supply filtering prevented internal EMI from reaching the power cord.)

Times have changed, however, and you often need additional high-frequency filtering throughout your power system. As clock speeds have increased, so has the high-frequency energy within the system. Using our rule of thumb of "20× the clock frequency," a 33-MHz clock has energy beyond 600 MHz, and a 66-MHz clock pushes that upper frequency limit beyond 1 GHz. High-speed systems also have high-frequency immunity problems with ESD energy in the 100- to 300-MHz range. Even the EFT has significant energy in the 50- to 100-MHz range. Without additional high-frequency protection, these transients can blast right through your power supply and find their way into your circuitry.

Here are some design tips for adding high-frequency protection to your power system:

(a) Add additional high-frequency filtering to your input power-line filter. Simple common-mode ferrite chokes work well because most power-line EMI above 30 MHz is common-mode noise. If you have a bulkhead EMI filter, mount the ferrite right behind the filter. If you are using an internally-mounted filter, then put the ferrite right next to the power-line entry point (**Fig 5**.) Be sure to use EMI ferrites—not those nice "low-loss" power-supply ferrites; and don't use more than two turns of wire through the ferrite core. Do not add extra "line-to-ground" capacitors at this point, because you may exceed safe current-leakage levels.

(b) Add additional high-frequency filtering on the power supply's output. We like to see high-frequency capacitors (typically 0.001 to 0.01 μF) at each power entry point on every circuit board, including backplanes. You can augment this filtering, if needed, by a single-turn common-mode ferrite on the power wiring as it leaves the power supply.

(c) Add high-frequency filtering to any auxiliary power ports (such as mouse and keyboard ports) (**Fig 6**). We've seen several units fail FCC radiated tests because of leakage through these ports. In this case, the unfiltered auxiliary outlet provides a sneak path for radiated high-frequency energy as

soon as a peripheral is plugged in. This is not a conducted problem but a radiated problem. You need the high-frequency filter to maintain the shielding integrity and to control unwanted radiated emissions.

Transient protectors block spikes

In many cases, you'll also want to include transient protection at the power entry point. Filters can attenuate small spikes, but large spikes require additional protection. As with filters, proper device selection and installation is very important.

Transient protection is mandatory in electrically dirty environments such as industrial controls or automotive applications where large power-line spikes are quite common. Transient protection is not as critical in commercial or even many military applications, where the equipment is usually provided with "clean" power through a power conditioner or UPS (uninterruptible power system.) However, if your products are destined for Europe, you'll need to include protection against the IEC 801.4 EFT (electrically fast transient) requirement. In this case, you can't depend on external conditioners for transient protection.

There are three types of transient protectors commonly used in equipment: arc devices, metal-oxide varistors (MOVs), and silicon devices. Each has its own advantages and disadvantages.

The arc devices are the most robust, but they're the slowest. They usually consist of a small gas-filled cartridge that ionizes above a preset voltage level. Upon ionizing, the voltage across the device actually drops to a very low level (**Fig 7**). As a result, arc devices do not dissipate much energy within the device, so you get a lot of performance out of a small package.

However, arc devices have two disadvantages. First, they are the slowest of the transient-protection devices, typically needing about 100 nsec or more to work. Even though this speed is more than adequate for lightning transients and motor/relay power spikes, it is not fast enough for EFT or ESD transients. Second, arc devices depend on phase reversal to "commutate" or turn-off, so they do not work on most dc power lines.

MOVs are faster than arc devices and are still quite robust. These devices consist of small granules of metal oxide (zinc is very common) that act like a bunch of small zener diodes under transient conditions. MOVs clamp voltage as shown in **Fig 8**. As a result, they must dissipate all the transient energy inside their package. Due to their granular design, MOVs can dissipate an amazing amount of energy in a small package—and can do so in 1 to 10 nsec.

Thus, MOVs are well suited to protect against lightning transients as well as EFT with its typical 5-nsec rise times. They are still a bit slow for a 1-nsec ESD transient, although some new multilayer MOVs appear to be fast enough for ESD transients as well. MOVs also wear out after a few million transients, but this is generally only a concern for applications requiring very high reliability and long life. MOVs are workhorses for most commercial and industrial applications.

Silicon devices are the fastest transient-protection devices. These parts consist of special zener diodes that are optimized for speed and energy dissipation. Like MOVs, they also clamp the voltage and do so very quickly, often in under 1 nsec. As such, these devices work well for all types of transients—lightning, motor, EFT, and ESD. They are a bit larger than MOVs for a given energy dissipation.

We prefer MOVs or silicon devices for most design applications, and we like arc devices for system-level protection. We also like the new modular filters with built-in transient protection and expect to see more of these products in the future.

As with filters, proper installation of transient protectors is critical. You need both common-mode and differential-mode protection (**Fig 9**). Keep the leads short to minimize lead inductance, which can slow the response, and install the transient protectors near the power input.

Minimize parasitic emission

This is a sneaky problem that can devastate a conducted-emission test. Fortunately, it's easy both to diagnose and to fix these problems. Anyone who has designed a switch-mode power supply is probably aware of the problem, but if you have not done so and don't plan for this problem, it will almost certainly get you. It's not a very common problem, but we see it several times a year.

Fig 5—High-frequency filtering on power supplies

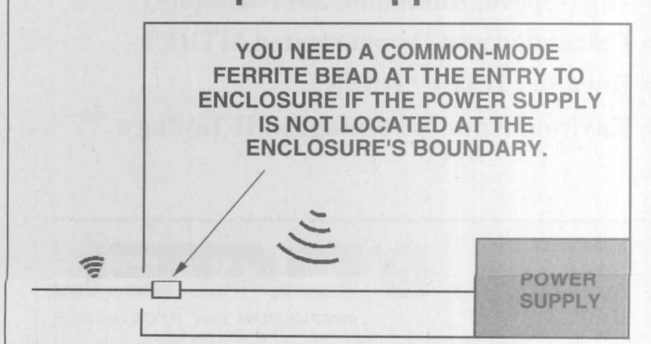
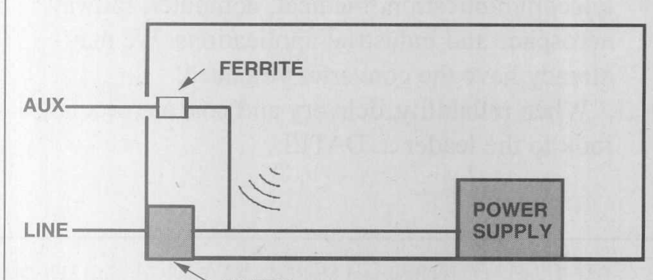


Fig 6—High-frequency filtering on auxiliary power ports



PROBLEM: AUXILIARY POWER LINE RADIATES
SOLUTION: FILTER AUXILIARY LINE WITH FERRITE BEAD

Fig 7—Arc devices crowbar the voltage

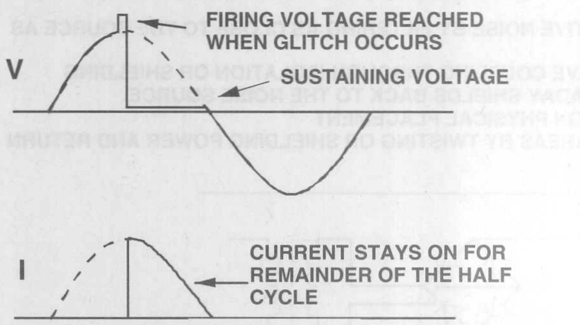


Fig 8—Clamp devices clip the voltage

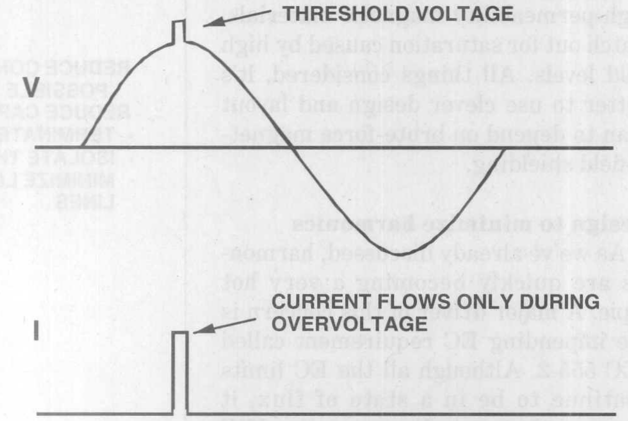


Fig 10 illustrates the situation. High-frequency energy is capacitively coupled from the switching circuitry to the cabinet. This results in common-mode current that returns via the hot and neutral power lines. These common-mode currents can cause you to fail FCC or VDE conducted-emission tests. (They can also cause interference problems in the real world.)

The problem is relatively simple to fix. The most likely coupling path is between the switching transistors and the cabinet. You can minimize this coupling by inserting a small Faraday shield between the transistors and heat sinks to intercept the capacitive currents. Such devices are available from several vendors. Another option is to float the heat sink electrically, which inserts extra series capacitance into the sneak path. However, this approach places the heat sink at the ac line potential and presents an electrical-shock hazard. Some power supplies use a rubber boot over the switching transistor and heat sink to prevent such a shock hazard.

Parasitic coupling can also occur across the switching transformer or even from wiring or other components that are close to the cabinet or a ground path. Small Faraday shields can help here as well. Careful physical placement of components can also minimize unwanted parasitic coupling. All of these approaches are critical in medical applications where leakage currents are measured in μA.

Watch out for other sneak paths. Several years ago we had a perplexing problem caused by the capacitive coupling from a "pulsed" inductor to an adjacent, but unrelated, heat sink. The noise was causing a VDE Class B emission failure. At first we suspected magnetic coupling from the inductor, but further investigations showed it was actually parasitic capacitive coupling. A small U-shaped shield connected to the electrically "cold" side of the inductor solved the problem.

Minimize magnetic-field emissions

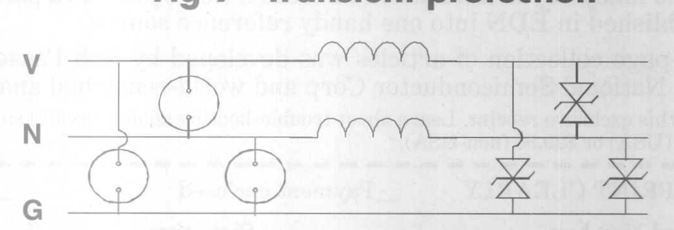
Magnetic-field emissions are a concern only if you are designing to meet VDE emissions or for certain military applications. Current FCC limits do not contain magnetic-field limits nor do the new EC requirements. On the other hand, with all the hysteria over magnetic fields, we would not be surprised to see mandatory magnetic-field emission limits in the future.

At the design and layout stage, it's really not too difficult to minimize magnetic fields anyway. However, it is very difficult to provide low-frequency magnetic-field shielding. So, if you want to minimize magnetic fields, it's best to get them out of your design up front to meet that objective.

The secret to eliminating magnetic fields is to minimize loop areas. Magnetic radiation is a function of four parameters: current, loop area, frequency, and distance from the "loop antenna." Of all of these factors, the loop area is the easiest to control and has almost no impact on normal operation. Keep high-current paths short and direct and keep their return paths as close as possible to the hot leads. Twisting wires (or transposing traces) is a very effective way to provide extra magnetic-field attenuation. (As a rule of thumb, we figure twisting is worth 20 dB of field attenuation.)

If you must shield, remember to use steel or other magnetic materials. Alu-

Fig 9—Transient protection



HYBRID PROTECTION INCLUDES ARC AND SILICON DEVICES:
- CLAMPS INCLUDE LARGE-GEOMETRY ZENERS AND METAL-OXIDE VARISTORS
- CROWBARS INCLUDE GAS-DISCHARGE AND ARC DEVICES

BOTH DIFFERENTIAL-MODE AND COMMON-MODE TRANSIENTS MUST BE ACCOMMODATED.

CHOKES LIMIT THE CURRENT UNTIL THE CROWBARS FIRE.

minum is virtually transparent to low-frequency magnetic fields. If you use high-permeability magnetic materials, watch out for saturation caused by high field levels. All things considered, it's better to use clever design and layout than to depend on brute-force magnetic-field shielding.

Design to minimize harmonics

As we've already discussed, harmonics are quickly becoming a very hot topic. A major driver of this concern is the impending EC requirement called IEC 555-2. Although all the EC limits continue to be in a state of flux, it appears that compliance to the IEC 555-2 power-line harmonic requirements will be mandatory on equipment sold in Europe after 1995.

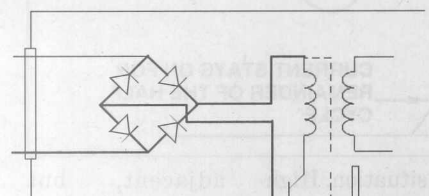
There are several ways to minimize harmonic-current distortion. Instead of direct rectification from the ac mains, you can insert an isolation transformer or use an inductor input filter. Both will provide series inductance ahead of the "bulk" capacitor to help filter harmonics. Unfortunately, these filters add considerable weight, which negates one of the prime advantages of switch-mode power supplies. Nevertheless, if you don't have a weight constraint, consider these simple additions to your design—you may be pleasantly surprised with the results.

Fortunately, the semiconductor makers are coming to our rescue with some new power-factor-correction ICs. These smart devices essentially cause the power supply to take current in several small pulses (spread over the cycle) rather than in one gulp. In high volume, these ICs should add less than $25 to the cost of smaller switch-mode supplies. Sure, power supplies are subject to intense cost pressures, but power-factor correction appears to be a good solution to a problem that is not dissipating. EDN

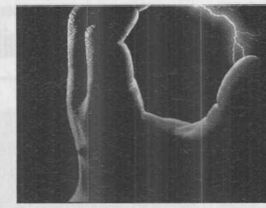
Fig 10—Reduction of parasitic coupling in power supply

REDUCE CONDUCTIVE NOISE BY FILTERING AS CLOSE TO THE SOURCE AS POSSIBLE

REDUCE CAPACITIVE COUPLING THROUGH ISOLATION OR SHIELDING
- TERMINATE FARADAY SHIELDS BACK TO THE NOISE SOURCE
- ISOLATE THROUGH PHYSICAL PLACEMENT
- MINIMIZE LOOP AREAS BY TWISTING OR SHIELDING POWER AND RETURN LINES



That wraps it up for EMI and power supplies. Even if you never design your own power supply, we hope you at least appreciate some of the unique problems faced by those who design power supplies for a living. And, if you know someone who designs power supplies, thank them for fighting all these problems for the rest of us; they'll probably be shocked by your attention. (Sorry, we just couldn't resist the pun.)



Chapter 10

Grounding...facts and fallacies

Grounding is probably the most important, yet least understood, aspect of electromagnetic interference control. Every circuit (even our hidden schematic) is connected to some sort of ground, so every circuit in the system can be affected by ground noise. You cannot leave grounding systems to chance—they must be designed right from the start!

We considered placing this article much earlier in this series on EMI but ultimately decided to put it toward the end. We figured if we put it first, many of you would just skip over it; after all, a ground is a ground right? But if you've read this far, you know that most EMI solutions heavily depend on proper grounding. In any event, we hope you are now ready and eager to learn a little more about grounding. We can't discuss every detail of grounding in one chapter (entire books have been written on the subject), but we can give you some basic insights on grounding—and how it affects your designs.

Most ground problems result from confusion as to what a particular ground is supposed to do. Contradictory guidelines such as single-point vs multipoint grounds can compound the problem. And there is always the temptation to improve the ground through isolation or by driving more ground rods into the earth. (The former approach can be unsafe, and the latter is often an act of desperation.)

Ground problems can range from individual circuits to entire buildings. Grounds can carry current levels from pA to kA, with frequencies ranging from dc to GHz. There is no single magic bullet for grounding. Like so many other EMI issues, you need to first understand the underlying problems, so you can apply the right solutions. Our focus in this chapter will be in those areas of grounding where electronic designers have some control—circuits, modules, and equipment.

Many types of grounds

One of the problems with grounding is the term itself. The word "ground" is vague and means different things to different people. To a circuit designer, it's the usually the "circuit voltage reference;" to a systems designer, it's often the cabinet or rack; to an electrician, it's the green-wire safety ground or the connection to the earth itself. As designers, we need both to define and to clarify exactly what we mean when we talk about grounding. Unless we're precise, we'll only add to the confusion.

One of the problems with *grounding* is the term itself...it's too vague.

So what is a ground, anyway? Many have tried to define a ground, but our personal favorite was put forth by Henry Ott some years ago: A ground is a low-impedance path for current to return to its source. As such, a ground is a vital part of the hidden schematic we've introduced earlier in this guide. The current path may not be the intended path, and there may be more than one path. In addition, currents from many different sources may share the same path, which can cause devastating EMI problems. These ground paths can not be left to chance—they must be designed in from the start.

You use grounds for many reasons, including power distribution, safety, signal integrity, lightning protection, EMI, and ESD. Most authors talk only of safety and signal grounds, but we prefer a slightly broader view. Even though all grounds provide a vital current-return path, they vary widely in their current levels and requirements. The two key parameters are the ground current's amplitude and frequency. We've summarized these parameters for different ground types in **Fig 1**. Now let's take a closer look at these different grounding needs.

Power grounds include both intended return paths (neutrals) and unintended return paths (safety grounds). Safety grounds are there to prevent electrical shock by providing an alternate path back to the power source (power service panel or transformer). Excessive ground current through this safety path opens fuses or circuit breakers in the event of an accidental short (**Fig 2**).

Safety grounds are required both by product-safety agencies such as UL or VDE and by electrical wiring requirements such as the National Electrical Code (NEC). In the US, safety grounds are typically connected to earth grounds (more on earth grounds will follow).

Power grounds usually handle many amps, but at relatively low frequencies such as 50 or 60 Hz. Neutrals must carry this current all the time the load is powered; safety grounds only carry the load current during a fault. These faults can last from msec to forever, depending on the fault current amplitude.

The main concerns for power grounds are maintaining a low resistance and providing enough current capacity. Low inductance is not needed for most power grounds.

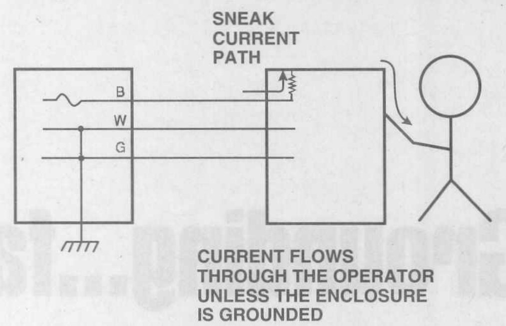
Fig 1—Different ground types

A ground may work over wide frequency and current ranges

- Power safety—50/60 Hz, 10 to1000A—seconds or minutes
- Lightning—1 MHz—up to 100,000A—tens of milliseconds
- ESD—300 MHz—10 to 50A typical—tens of nanoseconds
- EMI—dc to daylight—μamps to amps—nsec to years

Grounds are the sewer system of electronics

Fig 2—Safety ground example

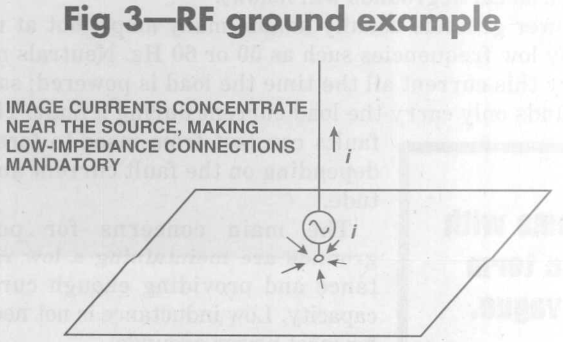


Lightning grounds provide a controlled path through which lightning currents can reach the earth. This is one case where you must have an earth connection because that connection is part of the lightning circuit. (Unless you are in an aircraft, but that's beyond the scope of this article. One of us was recently in an airplane as it was struck by lightning, and we can assure you that the current flow is very real and quite spectacular.)

Lightning grounds must handle upwards of 100,000A, but for just a few msec. Unless you are designing communications equipment connected directly to external antennas, most of us will see only lightning-surge currents on power lines or interconnecting cable shields. For equipment installed in a building, empirical data shows that these transient-surge currents are limited to about 2000A, with rise times of 1 to 10 μsec and durations of under 100 μsec. Even so, this is enough energy to damage your equipment if the grounds are not adequate.

The main concerns for lightning grounds are maintaining both low resistance and low inductance and providing adequate transient current capacity.

Fig 3—RF ground example



Circuit grounds provide a return path for both signal and power currents. Circuit grounds are often implemented as ground planes, ground grids, or ground traces on circuit boards. (Old timers will remember the chassis ground on vacuum-tube equipment.) We often provide independent circuit grounds for different types of circuits such as analog and digital grounds. If these different circuits communicate with each other, you need to connect the different grounds together at one point to provide a return path for the interface signals (analog-to-digital or digital-to-analog). Sometimes, you want complete isolation between these different circuit types. In such cases, you must couple signals between the circuits optically or with transformers.

Circuit grounds typically handle currents from mA to A, at frequencies ranging from dc to kHz (analog) or MHz/GHz (digital). The primary objective is to limit unwanted voltage drops across any ground paths. For this reason, circuit grounds are often referred to as equipotential planes. Unfortunately, you can only approximate this condition because the only way to ensure "zero" voltage drop is to have zero ground impedance or zero current flowing in the ground path.

These two concerns point us toward two key circuit grounding strategies: minimizing ground impedance over a broad frequency range or confining ground currents to predetermined ground paths. As we'll see later in this chapter, the first strategy is a common digital technique, and the second is a common analog technique.

EMI grounds provide a controlled path for EMI currents. EMI grounds usually serve other needs as well, such as circuit, chassis, or even safety grounds. The key here is first to decide where you want an EMI current to flow and then choose or provide the appropriate path. For example, if concerned about emissions, we are usually trying to intercept RF currents before they reach cables (antennas). We want the RF currents to return to the source circuit. Thus, grounding filters to the circuit ground makes sense for emissions problems. On the other hand, if concerned about immunity, we are usually trying to prevent RF or ESD currents from reaching vulnerable circuits, including the circuit ground. Thus, grounding filters to the external cabinet makes more sense for immunity problems. As we've said before, where you ground is as important as how you ground, particularly when dealing with EMI currents.

EMI grounds typically handle currents from μA to A, and from dc to microwaves. Thus, a key concern is maintaining low impedance over a very broad frequency range. Unlike power or safety grounds, high-current capability is usually not a prime concern for EMI grounds.

Electrostatic discharges, which are short in duration (1- to 3-nsec rise times) and high in amplitude (10 to 50A peak levels), are a special case of EMI. In this case, both low-impedance and

The ground as an electronic sewer

For many years, students of electronics have been taught to treat electricity like a fluid. You remember, voltage is like the pressure and current like the flow of fluid through the pipes. But once we use this vital electronic fluid, we no longer care about it and just flush it away with a ground symbol, right?

But that ground current doesn't just disappear into a void—it returns to its source by any path or paths available. A ground path is like a sewer, carrying electrons back to their source for recycling, just like water in a real sewer.

What are the attributes of a good sewer system, anyway? First, you need a low impedance in the main line—or things can back up all over the neighborhood, causing a gigantic mess. Second, you need low-impedance connections to the main line, or things back up at your own place. Third, you may need to provide different sewers for different needs. We really don't want the ingredients of a sanitary sewer to get mixed up with a storm sewer, particularly if that storm sewer may back up in the streets.

These characteristics sound like the attributes of a good electronic ground system as well: good, tight, low-impedance connections and perhaps isolated grounds to separate digital and analog return currents from mixing together and causing problems. Think about this the next time you're chasing a ground problem—you're just like Ed Norton on the old Honeymooners television show. And like Ed, it helps if you know where your sewers are and where they go.

One more point about grounds as sewers. A ground path is not a cesspool, in spite of what many people say about "dumping the noise into the ground" or other similar nonsense. Ground currents are always on the move, just like all that stuff in the sewer.

moderate current-carrying capability must be provided. Remember, at 1 to 3 nsec, ESD behaves like VHF energy in the 100- to 300-MHz range, so short leads and low-inductance straps are mandatory. You also need some metal thickness for ESD, because high ESD current densities can vaporize very thin metal coatings. Sometimes we use "soft" or resistive grounds to limit peak ESD current levels.

RF ground is a term you may hear if you work with radio transmitters or receivers. Communications antennas often depend on an RF ground or "image plane" to provide return-current paths to the antenna and to enhance the antenna's radiation pattern (**Fig 3**).

For example, a quarter-wave vertical antenna must be installed over a low-impedance ground plane because the ground plane actually provides a mirror image of half the antenna. Unless this local RF ground has low impedance, much of the RF energy dissipates as heat rather than electromagnetic radiation. Horizontal antennas are also affected by the local RF ground, but in this case the height above ground is the critical parameter and greatly affects the antenna pattern, which is why FCC and VDE emission tests are conducted above a ground mesh and why the antenna is moved up and down during the tests.

An RF ground's importance decreases with distance from the antenna. However, significant currents may be flowing in the RF ground close to the antenna. Thus, you must carefully control the impedance near the antenna. Note that RF or antenna grounds do not need an earth connection to function. Vertical antennas are routinely used on automobiles and airplanes without the benefit of earth connections. It is prudent, however, to provide fixed antennas with an earth-ground connection for lightning protection.

It should be clear by now that there are many types of grounds with many different functions. Often a single ground may serve multiple needs (safety, EMI, lightning), and at other times it serves only one need. Different rules apply to different grounds, so using one type of ground for another application may cause unwanted problems. Finally, grounds can provide sneak paths and may allow the current to follow multiple paths back to its source.

One more bit of advice: when discussing grounding with your colleagues, don't use the term ground by itself because it's too nebulous and open to misunderstanding. We suggest you add an adjective (such as signal ground, analog ground, frame ground, or safety ground) to describe more precisely the ground under consideration.

Key grounding issues

Now that we've looked at the reasons for grounding, let's examine some different grounding concerns, methods, and topologies.

Ground impedance: Simply stated, a ground must have a low impedance to minimize the voltage drop along the intended path and to prevent current from taking unintended alternate paths (see **box**, "The ground as an electronic sewer").

But what constitutes a low ground impedance? Like so many EMI issues, ground impedance heavily depends on frequency (**Fig 4**). For low frequencies, a heavy-gauge wire or other sub-

Fig 4—Ground impedance vs frequency

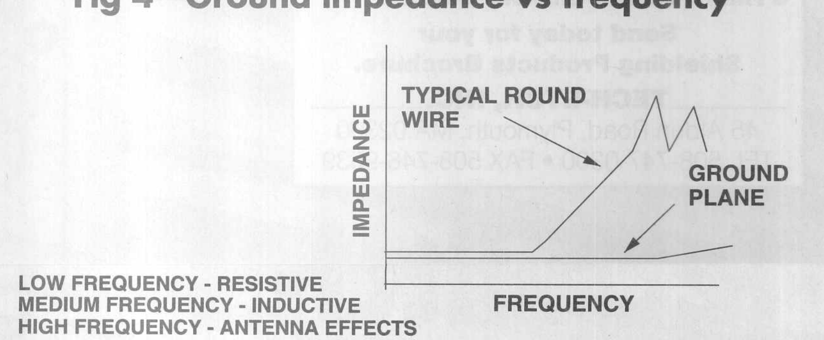


Fig 5—Ground straps

THE IDEAL GROUND IS AN INFINITE PLANE

CURRENTS FAN OUT TO INFINITY, BUT MOST CURRENT LIES WITHIN A 5:1 RATIO

THEREFORE, CURRENT DISTRIBUTION WILL NOT BE SERIOUSLY DISTURBED IF YOU CUT THE REMAINDER OF THE PLANE AWAY

A 10:1 STRAP PROVIDES ONLY A MARGINAL IMPROVEMENT

OFTEN A 5:1 STRAP IS NOT GOOD ENOUGH. AIM FOR 3:1

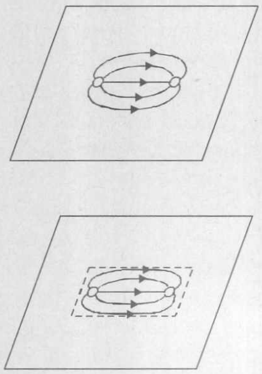
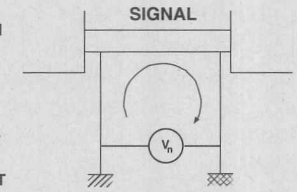


Fig 6—Ground-loop example

- A POTENTIAL LOOP EXISTS WHENEVER THERE ARE MULTIPLE CURRENT PATHS
- NOISE VOLTAGES THAT OCCUR FROM OPERATION OF NEARBY NOISY EQUIPMENT CAUSE CURRENT FLOW THROUGH THE SIGNAL RETURN PATH
- ALTERNATIVELY, THE LOOP SERVES AS AN ANTENNA TO RADIATED INTERFERENCE
- GROUND LOOPS ARE PRIMARILY A LOW-FREQUENCY PROBLEM
- GROUND LOOPS ARE DIFFICULT TO ELIMINATE AT HIGH FREQUENCIES



stantial conductor provides a low ground resistance. At about 10 kHz, wire inductance becomes a factor, and the inductive reactance (not resistance) limits current flow. At higher frequencies, standing-wave effects become a factor, and the impedance between two points can vary over wide extremes.

Once again, we see a division into two camps: low frequency below 10 kHz, and high frequency above 10 kHz. This is a key grounding issue; and as we'll soon see, very different (sometimes contradictory) rules apply to the two different camps. In fact, we often speak of optimizing our grounds for low or high frequency, depending on the objectives we seek to accomplish.

At low frequencies, just about any old wire will work for a ground, as long as it can handle the current. At high frequencies, you need to control the inductance. Solid metal planes have very low inductance, so they provide a practical high-frequency ground. These planes can be part of a circuit board, a chassis, or even the floor of a room. In fact, one of the reasons we use

ground planes on circuit boards is to lower the inductance, and thus the impedance, at high frequencies.

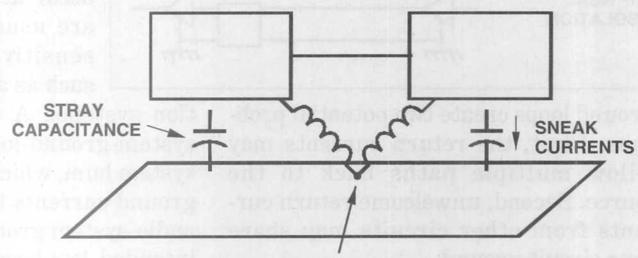
How large must such a plane be? As wide as possible, but never less than about 1/5 of the length of the ground path. (We actually prefer to limit ratio to 3:1.) The current distribution on a plane is such that most current lies within this boundary (**Fig 5**). We use this same criteria for ground straps (length-to-width ratios between 3:1 and 5:1) that bond different grounds together. Remember, flat straps alone do not make good grounds—low length-to-width ratios do.

A ground plane need not be solid. Ground grids are widely used for both circuit-board grounds as well as entire rooms. When used in a computer facility, these grids are often referred to as a signal-reference grid. To determine an upper frequency limit for a grid, we use a criterion of 1/20 wavelength as the maximum spacing between grids. By this criterion, a signal-reference grid with 2-ft openings is good to about 25 MHz, which is adequate to handle most spikes and transients seen by computer systems. (It is marginal, however, as an ESD ground with 100- to 300-MHz transients.) A 1/4-in. wire mesh (as used on many FCC and VDE test sites) is as good to over 2 GHz, and a 1/10-in. crosshatch on a circuit board is good to over 6 GHz.

Ground loops: This is an issue that causes much needless concern for high-speed digital-circuit designers. However, it can be a very critical issue for designers of low-frequency analog circuits. Ground loops can also be a key concern to systems designers, particularly with I/O and power circuits. You need to understand ground loops, but you need not fear them. For digital circuit boards, they are usually harmless.

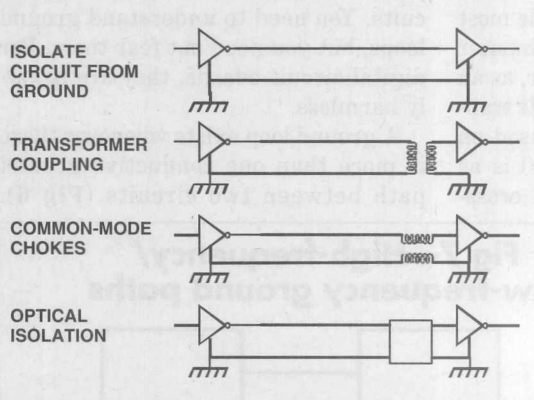
A ground loop exists whenever there is more than one conductive ground path between two circuits (**Fig 6**).

Fig 7—High-frequency/ low-frequency ground paths



A SINGLE-POINT GROUND TO A LOW-IMPEDANCE PLANE PROVIDES ONLY A LOW-FREQUENCY GROUND. HIGH-FREQUENCY CURRENTS FOLLOW STRAY CAPACITIVE PATHS

Fig 8—Breaking a ground loop



Ground loops create two potential problems. First, the return currents may follow multiple paths back to the source. Second, unwelcome return currents from other circuits may share your circuit ground.

In order for a ground loop to cause a problem, three conditions must exist. First, there must be a common shared ground path; second, there must be an unwanted source of current; third, there must be a circuit that is vulnerable to the voltage caused by this unwanted current. As we've mentioned earlier, you need a source, a path, and a receptor. You can fix the problem by attacking any of these three elements.

Most ground-loop problems occur at low frequencies and are usually associated with sensitive analog circuits, such as audio or instrumentation systems. A classic example of a system-ground-loop problem is audio-system hum, which is caused by power-ground currents that pass through the audio-system ground and modulate the intended low-level audio signal. (Ever fought this problem with your stereo?) Typical solutions include moving ground wires or providing dedicated ground conductors. This problem is the basis of the single-point, star, or isolated grounds, which are often touted as the cure for ground-loop problems. (We'll examine these different ground topologies a little later in this chapter.)

Separate grounds work well for audio frequencies but not for higher frequencies. In fact, they may not even be physically realizable. Thanks to the hidden schematic, wire inductance and parasitic capacitance actually encourage high-frequency currents to take alternate sneak paths (**Fig 7**). For high-frequency grounding, it is much more effective to minimize the ground voltage by lowering the ground impedance with ground planes and multipoint grounds. For example, digital circuit boards may have hundreds of small ground loops, but so what? We control the problem at high frequencies with a low ground-plane impedance.

We can also attack ground-loop problems by breaking the loop. Because

most ground loops are unintended common-mode circuits, placing a common-mode high-impedance point somewhere in that circuit controls the voltage caused by unwanted ground currents. **Fig 8** shows several examples of such high-impedance points, including floating the signal ground, optoisolators, transformers, and common-mode chokes. (Do not float the external chassis because this may cause safety grounding problems.)

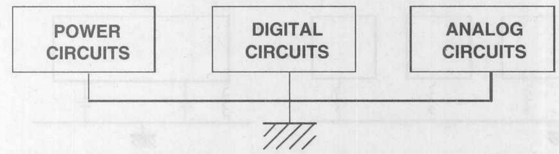
A word of caution if you float signal grounds: the ground may appear "dirty" if you look at the signal ground (measured with respect to chassis) with an oscilloscope. This is not bad news but good news. It means that most of the voltage is now between the two grounds (signal and chassis), and not across some internal circuit. We've solved several EMI problems in the field after hearing someone mention that they had cleaned up all the dirty grounds by bonding everything together. When we reverted to a single-point ground, the problems went away.

As we have already seen, single-point grounds are better for low-frequency circuits and threats. They prevent ground loops, and it's easy to steer individual ground currents at low frequencies. Single-point grounds are most effective at audio frequencies, from dc to about 10 kHz, although you can often push this upper end to about 1 MHz. We don't like to use single-point grounds above 1 MHz because of inductive and capacitive effects.

For higher frequencies, multipoint grounds to ground planes or grids are better. There are two secrets here. First, provide a low-impedance reference plane. Second, provide low-impedance connections to the reference plane. We use multiple ground-plane connections to minimize possible resonant conditions. We also like to use straps, rather than wires, with short, fat connections (length-to-width ratios less than 3:1). If you must use wires, keep them as short as possible. A 1-in. wire at 100 MHz has about 12Ω of inductive reactance and at 500 MHz, it's over 60Ω. Keep those ground leads short at high frequencies.

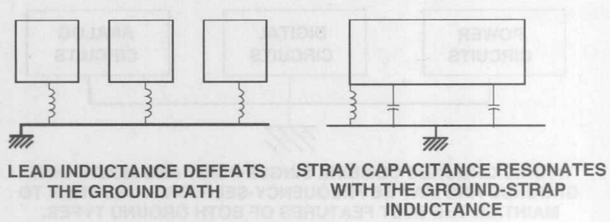
When we must accommodate both frequency ranges, we often use hybrid grounds. Capacitors provide high-frequency connections, and inductors

Fig 9—Single-point grounds



HYBRID GROUNDS COMBINE SINGLE-POINT AND MULTIPOINT GROUNDS AND MAY BE FREQUENCY-SELECTIVE. USE THEM TO MAINTAIN THE BEST FEATURES OF BOTH GROUND TYPES.

Fig 10—Hybrid grounds



provide low-frequency connections. **Fig 9** gives some examples. We've seen and used this technique on circuit boards, I/O connectors, and even on power-line filters. The key to success is to know both the frequency and the desired direction of your ground current path.

Earth grounds and isolated grounds

We often have cases where someone will suggest placing a ground rod next to the equipment to solve an EMI problem. Sometimes this solution works, but not because of the earth connection. (Ever measure the resistance of dirt?) It works because the added ground interrupts a sneak path for noise. If this earth-ground connection is isolated from the rest of the safety-ground system, it creates a serious electrical shock hazard and also violates the National Electrical Code. This is dangerous, so don't ever do it!

The misguided ground-rod myth is that noise can just be dumped into the earth. But remember, all currents flow in a circuit so if you send current down one ground rod, it comes up somewhere else: through power wiring, water and gas pipes, and building steel. At low frequencies, these noise currents wander all over the place. At high frequencies, noise currents may not go down the ground rod at all; they like to follow parasitic paths of their own choosing.

Another common myth is that circuits must have an earth-ground connection to function. But how many of you use an earth-ground rod with your battery-operated laptop computer? And how many airplanes use a *ground rod at 30,000 ft? A hundred* years ago, the earth was actually used as the return path for telegraph circuits, but today earth connections are needed only for safety.

We are not very fond of isolated grounds because of their potential misapplication and are very suspicious whenever someone suggests adding additional earth-ground rods. Several years ago, we had a case where a field-application engineer insisted that our client needed to add ground rods to prevent malfunctions to his company's equipment. Our investigations revealed an inferior product design that we were able to overcome with external isolation transformers, not ground rods. The solution was also safe and satisfied the National Electrical Code.

Design guidelines for grounding

Now that we've examined both the physics and the philosophies of grounding, we'll provide some specific grounding-design guidelines.

Don't compromise safety grounds: We've already preached about this point and realize that no engineer wants to design unsafe systems. The causes of most grounding safety problems are ignorance of the potential hazards or not considering the ramifications of a design change. Hopefully we've shed some light on some of these problems in this article.

For equipment designs, just meeting the appropriate safety-agency requirements will keep you out of a lot of trouble. If you have safety questions, we suggest getting some guidance from a cognizant safety engineer early in the design. Most large companies have an internal safety expert; many safety engineers are in private practice. Many EMI test labs provide product-safety testing and consulting services. Don't hesitate to call the product-safety agencies directly; they are obviously very concerned about designing safe products.

Grounding analog circuits: As we've already seen, single-point grounds are better for low-frequency, low-level analog circuits. The primary objective is to prevent large ground currents from other noisy circuits (digital circuitry, motors, relays, power sources) from sharing a sensitive analog ground path. You must avoid ground loops with all sensitive low-frequency analog circuits. Fortunately, at the low frequencies of most analog circuits, it is easy to control both intended and unintended currents with single-point grounds.

How quiet your analog grounds need to be depends on the sensitivity of the analog circuits. The more sensitive the circuit, the more vulnerable it is to ground noise. It's a matter of signal-to-noise, or in this case signal-to-interference. Thus, a low-level analog stage that is looking for 10-μV signals is much more vulnerable than a high-level stage dealing with 10V signals. For low-level analog circuits, you need a very clean ground. For higher level analog circuits, ground requirements are less stringent.

As a rule of thumb, we like to keep our analog ground voltages less than the smallest increments of signal voltage we need to function. A 10-bit A/D or D/A converter operating over a 0 to 5V range has approximately 1 mV of resolution, so we shoot for less than 1 mV of ground noise. For a 10-μV signal from a sensitive transducer, that same 1 mV of noise would be way too much.

Digital circuits can be particularly hard on their analog brethren. Digital circuits tend to be noisy and often have many mV of ground bounce. These mV digital noise levels can easily jam μV-level analog circuits if they share the same ground. High-speed CMOS logic is the worst offender from higher peak switching currents. Earlier in this guide, we saw that high-speed CMOS caused higher radiated EMI emissions for the same reason.

Thus, it is prudent to provide separate analog and digital grounds. For very sensitive analog circuits, you may want to provide separate analog and digital power as well. You still need to join analog and digital grounds together to provide a signal-return path for D/A or A/D circuits. Join digital and analog grounds at one, and only one, point. This point can be on the circuit board, or at the power supply, but not

both locations. Sometimes it pays to add a small resistor (typically 10 to 100Ω) or a ferrite bead between the analog and digital grounds. These measures are particularly effective at higher frequencies where parasitic capacitances can try to form a new ground loop.

In extreme cases, you may want to completely isolate your analog and digital circuits and have no common power or ground connections. You can do this through optical isolation or transformers. Most routine microprocessor analog/digital circuits do not need this complete isolation, but it may become mandatory when dealing with very sensitive instrumentation circuits.

Grounding digital circuits: For digital circuits, we prefer multipoint grounds and ground planes. Because we're dealing with high frequencies, the primary objective here is to lower the ground-path impedance through brute force. Single-point grounding does not work well with most digital circuits because the parasitic inductance and capacitance severely alter the ground paths anyway. As we saw earlier, ground loops are usually not a digital problem, particularly if you maintain a low ground-plane impedance.

How quiet must you make your digital grounds? Fortunately, they don't need to be as quiet as most analog grounds. Digital circuits have noise margins in the hundreds of mV, so they can typically withstand ground-noise gradients of tens to hundreds of mV. The bad news is that digital grounds must function over a wide frequency range, often well into hundreds of MHz. Thus, ground planes are best for digital circuits.

If a system resides in a metal enclosure, we prefer to make multiple high-frequency connections between the circuit-board ground and the cabinet. If low-frequency isolation is needed, then the connections can be feedthrough capacitors. Otherwise, short, direct connections are best.

Fig 10 shows an example of digital circuit-board-to-chassis grounding, which is popular with personal computers. This is a hybrid scheme, providing many low-inductance, high-frequency connections but maintaining only one low-frequency connection. We've used this approach on high-speed designs with good success.

I/O grounding: We've already touched on this subject in our earlier discussions on cables and connectors, but it's worth looking at again. The I/O section is where the circuits (unintended transmitters and receivers) meet the cables (unintended antennas), and proper grounding here can mean the difference between EMI success and failure.

If the system has a shielded cabinet, then we ground all I/O filters to the cabinet as close to the point of penetration as possible. The best situation is to use bulkhead-mounted filtered connectors with the filter-ground connected directly to the cabinet through the cabinet shell. This approach allows the filter to strip off any EMI as it tries to enter or leave the system.

An alternate approach that is becoming quite popular is to incorporate a separate I/O ground on the circuit board (**Fig 11**). In this case, filter capacitors connect to this separate ground, which in turn is connected to the chassis. Even though not as good as the bulkhead approach, this scheme can still be very effective in commercial and industrial designs. It also costs less than bulkhead filters, and is easy to manufacture. Once again, clever design can pay EMI dividends.

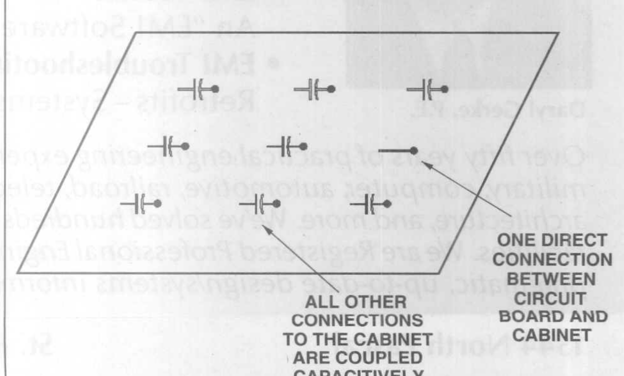
A special I/O grounding issue we often see deals with coaxial LAN connectors, where the coax connector shell is floating from the chassis, which is done to prevent 60-Hz currents from flowing on the cable under power-fault conditions. As LAN cables are often distributed all over a facility, they are much more vulnerable than other interfaces to this special ground-loop problem. Unfortunately, this floating shell allows high-frequency energy, such as ESD or RFI, to enter and leave the system unimpeded. The solution is to add a small capacitor (0.001 to 0.01 μf) between the cable shield and cabinet. Several vendors now offer connectors with this capacitor built into the connector. If you are designing a systems with a floating LAN connector, we advise using the capacitive connector to control the high frequencies. This is one more example of hybrid grounding.

Internal module grounding: A typical system may include a number of modules in enclosures such as a card cage, disk drives, power supply, cables, and maybe even a printer or CRT display. Here are some guidelines for grounding these modules:

First, we recommend mounting the modules on a ground plane and then routing the interconnecting wiring close to this plane to minimize unwanted cable-loop areas. (Don't route the cables in mid-air.) This will help control high-frequency EMI, such as digital noise or ESD. This ground plane can be a metal cabinet or can be a separate base plate or structural member. In any event, it must meet the requirements for a low-impedance, high-frequency ground. (Length-to-width ratio of 3:1 or less, no unbonded seams, etc.)

Second, all modules should be connected to the ground plane, either directly or through a short, fat ground strap (length-to-width less than 3:1). The circuit boards in the module do not need to be connected directly to this chassis ground, although digital cir-

Fig 11—Printed-circuit-board example



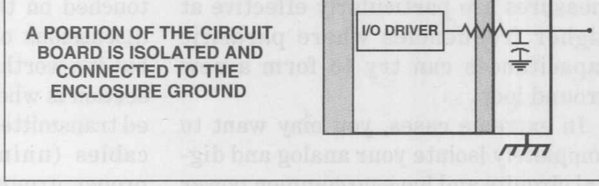
cuits can be connected through multiple connections if desired. We recommend having separate single-point grounds for analog circuits and for any motor or relay circuits. If these different grounds (analog, digital, motor, relay) must be connected to provide a signal return, this should be done at only one point.

Third, make sure you have a proper connection between the chassis and the green-wire safety ground on the power cord.

Design your ground: Don't leave grounding to chance. We often find it useful to construct a ground map, starting at the circuit level and working all the way out to full system level. The objectives are to identify both the grounding needs and all the various types of grounding paths. A ground map can also be useful in troubleshooting because so many EMI problems are related to grounding.

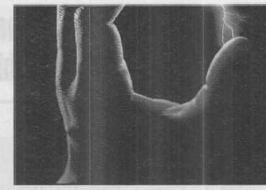
To construct a ground map, first identify the different types of grounds: safety, EMI, circuit (digital, analog, motor, relay), module, cabinet, etc. Then examine areas where the same ground path serves multiple functions. Look for sneak paths and multiple single-point grounds. Assess all ground connections for both current amplitude and frequency needs to

Fig 12—Separate I/O ground



see if they are adequate. Just building a ground map can often point out critical ground problems—as well as their solutions. EDN

That wraps it up for grounding. We've seen that grounds aren't all that mysterious after all. Grounds are simply the return paths for currents that are trying to find their way home. However, there are many types of grounds that serve different needs, which often leads to conflicting design rules. We've seen that single-point grounds work best for low-frequency analog circuits, and multipoint grounds work best for high-frequency digital circuits. Sometimes you need hybrid grounds to cover all the bases. Finally, never compromise on safety grounds.



The Designer's Guide to Electromagnetic Compatibility

Chapter 11

EMI testing...if you wait until the end, it's too late

Early in this series, we made it clear that our focus was on EMI design issues and not EMI test issues. We even gave you some insight into the differences between the EMI design and EMI-test engineering disciplines. But like it or not, most designs today are subject to some kind of EMI tests, so you need at least a nominal understanding of EMI product testing.

Don't worry. We are not going to burden you with all the subtle intricacies of how to measure site attenuation, calculate coaxial-cable balun losses, or interpret antenna factors. These details are best left to the EMI test experts. Our emphasis here will be on test issues that are important to you as a design engineer. These issues include how to prepare for formal EMI-compliance tests, EMI engineering tests that you can do in your own lab, and even some thoughts on EMI-audit tests.

Why do we need EMI tests, anyway?

In a nutshell, we need EMI tests because EMI predictions and analysis alone are not adequate to assure compliance with EMI regulations or EMI objectives. Or as Dan Hoolihan of Amador Product Services, an EMI test expert likes to say, "EMI testing is done to keep the EMI design consultants honest." Seriously, Dan points out, if EMI design were simple and straightforward, EMI testing would not even be necessary. Instead, we'd all just use a design check list to show we met the EMI requirements.

As we saw in the first chapter in this guide, EMI is not complicated, but it is complex. There are many variables to every EMI situation, and it's impossible to cover all the possibilities with design or analysis tools. Perhaps, someday it will be feasible to model every EMI possibility on a computer, but we don't think we'll see that happen in our lifetimes. Thus, testing is the crucial final step in designing for EMI.

Three categories of EMI testing

We like to divide EMI testing into three categories. These are: compliance, engineering, and audit tests. Each of these categories has different needs and objectives. For example, you run compliance tests to prove that your design meets the appropriate EMI requirements so that they require very precise and absolute measurements. Engineering tests, on the other hand, aim at uncovering potential problems or assessing fixes, which can be done with less precise and relative measurements. Audit tests aim at proving that the EMI design is still intact, and they can often be done on a less precise sampled basis.

EMI compliance tests are the tests most designers think of when we mention EMI tests. The objective of EMI compliance testing is to verify that a product meets appropriate EMI requirements (as discussed in the second chapter). You normally run compliance tests at the conclusion of a design but before selling or delivering the product. (The applicable requirements must be determined at design commencement. If you've waited until now to determine your EMI requirements, you are probably in deep EMI trouble.)

Most of you will use outside organizations, such as an independent EMI test laboratory or an in-house EMI test laboratory to perform EMI-compliance testing. EMI-compliance testing is very precise and requires expensive equipment and experienced personnel. Most EMI labs have also been certified by independent agencies such as NVLAP (National Voluntary Laboratory Accreditation Program), assuring high levels of quality control. Most labs are also up to date with the latest developments in EMI testing and regulations. All this capability takes years to obtain, so it's unlikely that you'll be doing your own compliance tests.

As a designer, you don't need to fear EMI compliance tests, but you do need to prepare for them. Compliance testing is expensive and billed by the hour, so you want to be as efficient as possible. Here are some guidelines on how to get the most out of your compliance tests with the least amount of pain.

First, define your objectives, and develop a plan. We've mentioned this so many times before in this guide that we're starting to sound like a broken record. Nevertheless, we still see cases where equipment is sent to a test lab

Most designs today are subject to EMI tests, so you need at least a nominal understanding of EMI product testing.

The Designer's Guide to Electromagnetic Compatibility

EMI design reviews

An ounce of prevention is worth a pound of shielding. Many of our clients now include EMI design reviews as a part of their design process. They have discovered that the earlier you address the issues, the more options you have to solve the problems.

It doesn't take a lot of time to do such a review. We find that a day or two is more than enough time to go over all aspects of the design, including the pc design and layout, I/O, power supply, interconnections and cables, and mechanical packaging. The EMI review can be independent of other design reviews, but you do need someone who is experienced in EMI design issues to conduct the review.

The best time for such a review is near the start of a project. Just before or during the first pc-board layout is ideal, as most design concepts are solid at this point. A special note to military designers: You need to review the design during the proposal stage because that is when many of the key design decisions are made. Design reviews save money, too. Remember, each time you fail an EMI test, it can easily cost you $25,000 to $50,000 for rework and retest.

without the designers even knowing what tests are needed. Those same designers are often the most vocal when their equipment fails. If you have no plan, then you plan to fail—it's that simple.

We recommend a written test plan. This need not be complicated, and even a simple outline is better than no plan at all. The test plan should identify all tests to be performed and should list the specific test objectives (such as FCC Class A or ESD per IEC 801.2 to 8-kV contact/15-kV air discharge). The plan should also describe the specific configurations to be tested and should list all the necessary peripherals and cables.

For emissions tests, you should identify every oscillator frequency in your system, including switch-mode power-supply frequencies. Better yet, you should generate a list of the first 50 harmonics for each oscillator. You'll find this list a big help during emissions testing if you need to identify the source of a specific high-frequency failure. You can quickly compute these harmonics on a spreadsheet and then sort the list for easy tracking.

For immunity tests, you need to establish failure criteria. You should determine what constitutes a failure and how you will identify it. Incidentally, multiple failure criteria are perfectly acceptable. The IEC 801 series includes examples of different failure modes.

You may also need to develop special software for emissions and immunity tests. For emissions tests, you need to be sure to exercise all peripherals, hard drives, etc. (PCs already have specific software functions spelled out in some emissions test procedures, such as the "scrolling H" pattern used on video terminals.) For immunity tests, you need to exercise the entire system, and you may even want to provide some special routines for error trapping or identification.

Two conditions can make immunity testing difficult. The first is if you are unable to detect when an error has occurred. The second is if internal errors can stop the system, forcing you to reboot every time an error occurs. We had one case where it took 10 minutes just to restart the system after each error. The testing proceeded rather slowly.

After you have developed your plan (even if it's crude or incomplete), you need to review it with a test engineer. Be ready for some give and take. At this stage, your test plan is a tool to facilitate communications and understanding about what needs to be accomplished and how those needs will be met. Ask questions and give serious heed to the test engineer's advice; remember, this is what he or she does for a living. Actually, you will find that most test engineers will be very pleased to work with you if you've already written a test plan. The plan will make both of your jobs easier as well.

Once you have your test plan in place, your next step is to put the system together and check it out. Configure your test system and double check everything. Install all peripherals and all test software, and make sure everything works as it should. Better yet, run the system for 24 hours or more to burn in your test system. Make backup copies of your test software too. There is nothing worse than having a system crash in the middle of a test and not being able to continue because the only copy of the software is dead.

Sometimes it pays to configure several systems for testing. This can be very effective if you are concerned about the cost or necessity of EMI fixes, such as cabinet shielding and extra filtering. In those cases, we recommend the "ABC" approach, which uses three systems. The "A" system has minimal EMI components, the "B" system has moderate EMI components, and the "C" system is as bulletproof as we can make it. We then test all three systems, in the following order:

We begin testing with the A system. If it passes (most of the time it won't), we're home free with a minimal design and minimal test expenses, and everyone is happy.

If the A system fails, we immediately switch to the C system. If this system passes (most of the time it will), then at least we know we can meet our EMI objectives. If the C system fails, we don't even bother with the B system because we know it will also fail.

But if the C system passes, we then switch to the B system. If the B system passes, we can either quit or we can experiment by removing selected components to reduce system costs. If the B system fails, we can either add components to system B or we can remove components from the C system. After all, we know the solution lies between these two boundaries.

We've found the ABC approach to be very helpful for addressing management and marketing questions, such as: "Do we really need to shield the system?" and "Do we really need those expensive EMI filters?" There is noth-

ing like hard test results to answer these questions. Test results eliminate a lot of needless arguing and agonizing over what needs to be done. The ABC approach also provides a ready source of spare parts if you need them at the test site. Most important, the "ABC" approach gives you a high probability of success on the first try at the test lab.

One final piece of advice—use new cables and connectors for all peripherals. In earlier articles, we've repeatedly stressed that cables and connector are a leading cause of EMI failures, particularly for radiated emissions and immunity. We've seen cases where many hours of expensive test time were wasted because of poor cables and connectors. Don't end up like one of our clients, who was admonished by a colleague saying "I told you to bring the new cables, not the old ones."

Now that you have both your test plan and your test system (or systems) in place, you are ready to go to the test lab. (You did make reservations in advance, didn't you?) Most test facilities are booked several weeks to several months in advance, depending on the tests to be done and the backlog. Don't wait until the last minute to book your test time.

If you are a cognizant design engineer, you should attend the EMI tests. First, you can make sure the system is working and properly configured. Second, you can fix the system if it breaks. Third, you can try some fixes if the system fails the EMI tests. And fourth, you might even learn something that will help you in future designs. This is not the time to "throw the design over the wall" and let someone else worry about testing your creation.

If you are unsure of your EMI-fixing or -troubleshooting abilities, we recommend taking along a colleague who has EMI-design experience. (Or bring along your favorite EMI consultant; we often go along with clients when they are testing new products.) The reason for this is that good EMI-test engineers are not necessarily good EMI-design engineers. *Most EMI-test engineers* can offer suggestions if you fail, but unless they have years of design experience, they may be unable to help you with detailed design questions. On the other hand, don't rebuff their advice, as they very often give you effective, proven solutions to your EMI problems. Remember, EMI testing is their business—each day, every day.

Here is some blunt advice about the EMI test technicians. These men and women are like the sergeants in the military, and they really know their stuff. Don't be a hotshot and try to impress them with your design abilities or your EMI knowledge. You want and need their help and support, not their disdain. If you fail a test, don't argue and gripe about the test procedures. Ask for suggestions and advice instead. This may sound trite, but we've seen too many cases where the designer alienated the very people who could best help. Don't let that happen to you.

Finally, go to the test lab with a positive attitude. View it as a chance to learn and to validate your design. With good preparation and a good attitude, you might even find that you enjoy EMI testing. We usually do.

What to do if you fail

First of all, don't panic if your system fails the EMI tests. Most designs don't make it on the first try anyway. We advise our clients to plan for at least three trips to the test lab unless they have done a lot of precompliance testing, which we'll discuss shortly. Like firing a cannonball, the first shot at the test lab is often done to determine the range.

If you have one or two failures that are close to a limit, it pays to try and fix the problem on the spot. If you have many failures or are way over your limits, then you should concentrate on gathering as much useful information as you can. Don't just stop the test and do nothing. This is why we advocate that you, as the designer, should attend the testing. There is nothing more frustrating that finding out you have failed a test, but you have no further information. If you are there, you can observe and try different things. Even a few minutes can give you valuable insight into the problems.

If the failed test is for radiated emissions or susceptibility, make sure all the cables and connectors, as well as joints and seams on metal cabinets are tight. Try disconnecting cables one at a time to see if the levels change. Next, try de-energizing parts of the system (peripherals, boards, circuits), and record the effects. Try to identify unwanted sources or antennas.

If the failed test is for conducted emissions or susceptibility, make sure all filters are properly installed and grounded. Try to determine if the failure is common or differential mode. You can do this quickly with a current probe by checking each conductor individually and then in groups. Check for parasitic coupling in the power supply—a likely source of conducted emissions failures.

If the failed test is for ESD or EFT and you have a computer-based system,

Fig 1—Radiated emission test configuration

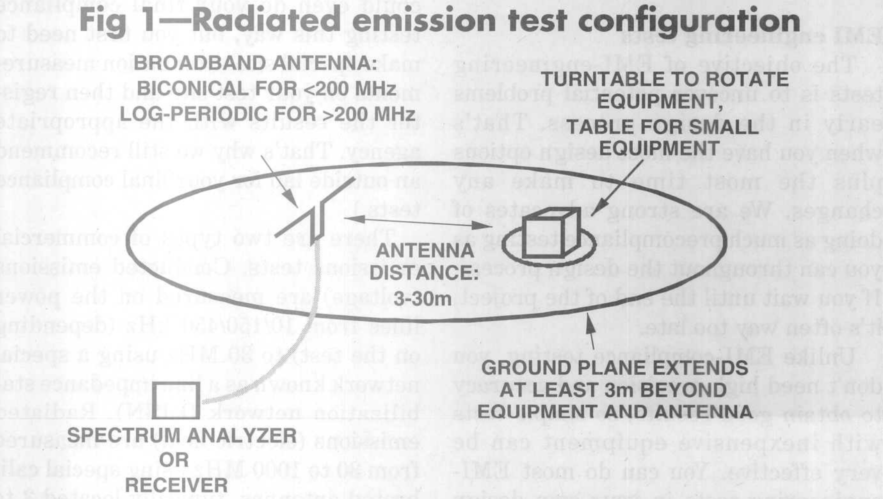
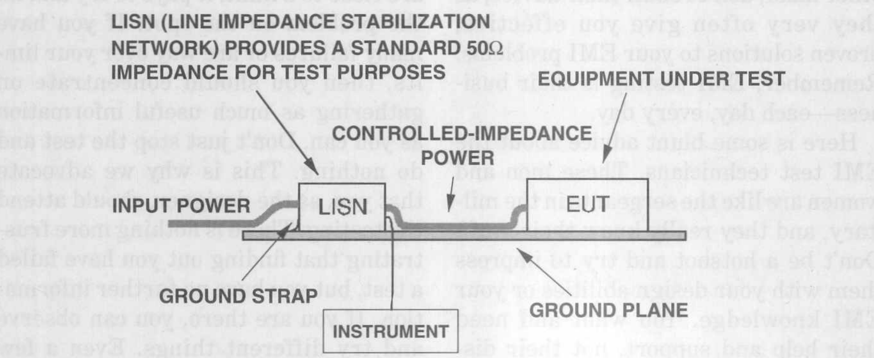


Fig 2—Conducted emission test configuration



try to determine how the system is responding to unexpected pulses. Is the system being reset? Is memory being altered? Is the I/O being clobbered? What about a false interrupt? Quite often, computer-based systems are trying to tell us what is wrong with them, if only we would listen.

Ask the test engineers and technicians for their ideas and suggestions. Remember, they see these problems every day. If they suggest a fix, try it out, even if it is not practical from a design standpoint. After all, if it works, then you can decide how to best implement such a fix. You're a designer, right?

Finally, even if you can't fix things, gather as much information as you can, and keep copious notes. Then, go have your favorite beverage and forget about it. No sense in brooding, and there will be time to fix the problems tomorrow when you get back to the design lab.

EMI engineering tests

The objective of EMI-engineering tests is to uncover potential problems early in the design process. That's when you have the most design options plus the most time to make any changes. We are strong advocates of doing as much precompliance testing as you can throughout the design process. If you wait until the end of the project, it's often way too late.

Unlike EMI-compliance testing, you don't need high precision and accuracy to obtain good results, so simple tests with inexpensive equipment can be very effective. You can do most EMI-engineering tests in your own design lab. In most cases, you will still want to use an outside lab for your EMI-compliance testing, but with EMI-engineering tests you can both minimize your EMI risk and maximize your chances for EMI success. Here are some thoughts and guidelines for EMI engineering tests.

Emission prescreening

If you are designing equipment that must meet commercial radiated or conducted emission limits, these tests make a lot of sense. (These are probably the most common EMI tests done today.) For less than $20,000, you can equip yourself with enough test capability to almost guarantee that you'll pass your next FCC, VDE, or CISPR tests. Given testing costs of several thousand dollars a day, if you save even a few days of retesting, you'll soon pay for this equipment. (In theory, you could even do your final compliance testing this way, but you first need to make special site-attenuation measurements on your test site and then register the results with the appropriate agency. That's why we still recommend an outside lab for your final compliance tests.)

There are two types of commercial emissions tests. Conducted emissions (voltage) are measured on the power lines from 10/150/450 kHz (depending on the test) to 30 MHz using a special network known as a line impedance stabilization network (LISN). Radiated emissions (electric field) are measured from 30 to 1000 MHz using special calibrated antennas, typically located 3 to 10m away from the equipment under test. For more details, we recommend IEEE C63.4, "Methods of Measurement of Radio-Noise Emissions from Low-Voltage Electrical and Electronic Equipment in the Range of 9 kHz to 40 GHz." Here is a list of equipment you'll need:

- Spectrum analyzer—A small portable unit works well, as long as it covers 10 kHz to 1 GHz and has reasonable sensitivity. Several test-equipment vendors (Tektronix, Hewlett-Packard, and IFR, to name a few) make portable analyzers that work well for these types of tests. Some even offer EMI options that include the correct bandwidths for making measurements. It's best to get one with an optional "quasi-peak" detector, the type of detector specified in the FCC, VDE, and CISPR limits. (Not everyone offers this option, so be sure to check.) A really nice feature on at least one portable analyzer is the ability to preinstall antenna factors, giving you a readout of electric field levels directly on the screen. Finally, get an analyzer that offers a computer interface, which can simplify data reduction and reporting.
- Antennas—You need only two antennas: a biconical to cover the 30- to 200-MHz range and a log-periodic to cover the 200- to 1000-MHz range. You should also purchase a nonconductive tripod to hold these antennas.
- LISN—You'll need one of these to perform the conducted power-line emission measurements. There are several types of LISNs, and the type you need depends on the test that you'll be doing (FCC, VDE, or CISPR) and the class of test (A or B). Be sure to check with the vendor to make sure you have the right type.
- Miscellaneous—Cables, connectors, high-frequency clamp-on current probes (useful for checking for currents on cables and power wiring), and a set of sniffer probes (useful for detecting shielding leaks and even locating hot spots on circuit boards).

Fig 1 shows a typical radiated-emissions-test configuration. Note the

open area, the ground screen, and the antenna location. If you have some open space, (an open area in a parking lot works) you can do the tests at 3m, but if you are confined, you can do the tests at 1m. We've done 1m measurements in the design lab with acceptable results for engineering tests. At the closer distance, you simply decrease the measurement (or increase the limit) by 10 dB to account for the difference between 1 and 3m. What about ambient levels? You can either turn your equipment on and off to see if the level remains, or you can save a scan of the ambient and then let the spectrum analyzer do a "B–Save A" display, which subtracts the recorded ambient from the reading.

Purists might argue with our test approach, but remember, this is for engineering use, not compliance. For engineering tests, it's more important to pick a method and stick with it, so that you can determine if you are making improvements as you make changes. One caution: keep away from metal surfaces that can reflect the energy and cause erroneous readings. For that reason, these tests should not be done in a shield or screen room. Use an open area instead.

We generally use an abbreviated set of radiated-emission tests. Instead of measuring every 45° around the unit under test, we usually do just four measurements at 90° intervals. We don't bother to raise and lower the antenna, but we measure 1m from the floor. We do measure both horizontal and vertical configurations, however. You can make the full set of tests if you want, but it will take more time. If we find that all our measurements are 6 dB under the test limit (as adjusted for the test distance), then we have a high confidence that we will pass at the test lab. In a pinch, you can go with a 3-dB margin, but anything less is likely to fail.

Fig 2 shows a typical conducted-emission test. Note the use of a metal ground plane and that the LISN is solidly grounded to the ground plane through a bond strap. This may seem insignificant, but it isn't. In fact, failing to properly bond the LISN to a ground plane is a very common mistake, and it causes very erroneous measurements. Now that you know about the problem, you can do it right.

Because conducted emissions are a composite of both differential- and common-mode currents, it helps if you can determine which mode predominates at any given frequency. Some LISNs have optional networks to help determine this, but a very simple method uses a clamp-on high-frequency probe. If you clamp the probe over a "hot" and "return" line at the same time and the current drops to zero, then the emission current flow is differential. If the current level increases when you clamp the probe over the two conductors, then the current flow is common mode. As we have seen in earlier articles, this distinction is important because different emission modes require different filtering techniques.

As you can see, setting up a precompliance test site for radiated and conducted emissions is neither expensive nor difficult. You can use such a site for screening before the first compliance tests and for troubleshooting as well. We have many clients who use such an approach and, as a result, have good success rates when they make their final compliance tests at an EMI test lab. Incidentally, if you don't want to set up your own facility, many test labs now offer "quick scans" using similar techniques. The data is not official, but it is much cheaper and faster than running a full-blown compliance test.

ESD prescreening

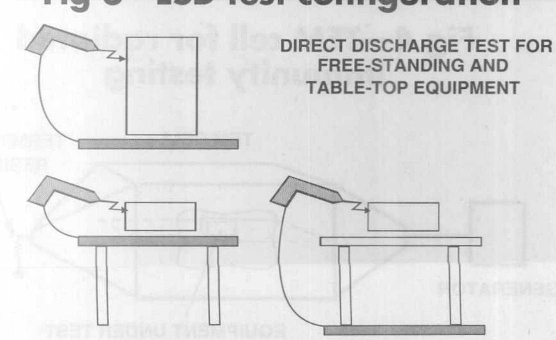
ESD-prescreening tests are another good candidate for engineering-level tests. For under $10,000 you can purchase the equipment that lets you duplicate all but the most severe ESD tests in your own lab. With the advent of the European Community ESD requirements plus ESD problems in the real world, this testing is becoming very popular. Even if you do not legally need to meet these limits, we think it's a good idea to test for ESD. (If you don't test for ESD and your competitors do, they will have the edge in product quality.)

We recommend that you follow the ESD-test procedures of IEC 801.2 (Electromagnetic Compatibility for Industrial Process Measurement and Control Equipment, Part 2: Electrostatic Discharge Requirements). This is the test document specified by the European Community, so if you are planning to market in Europe after 1995, you must meet this requirement anyway. Other organizations, such as the United States Food and Drug Administration (FDA) are adopting this standard for medical devices. The only reason we see not to use this standard is if your industry has a specific alternative ESD test.

Fortunately, there are several inexpensive ESD testers available from vendors such as KeyTek, Schaffner, and Haefley. Important parameters include the ability to perform both contact and air-discharge testing, voltage levels of 10 kV contact/15 kV air discharge (you don't need to go higher for most engineering-level tests), and conformance to the IEC 801.2 standards. Features that are convenient, but not necessary, include multishot capabilities, digital readouts, and shot counters. We've used a simple portable ESD tester for several years and have been very pleased with the results. Best of all, it doesn't look like a great big gun, so we don't get hassled when it's in our carry-on airline baggage.

Fig 3 shows a typical ESD-test configuration for a tabletop piece of equipment. This is right out of IEC 801.2, so if you need more detail, see that docu-

Fig 3—ESD test configuration



ment. Here is the order we go through for an ESD-engineering test:

First, we make our indirect discharge tests. We discharge to the ground plane under the equipment at about 0.1m from all sides of the equipment. Then we discharge to the vertical coupling plane, located 0.1m from all four sides of the equipment. We usually set the ESD gun for 20 pulses/sec and zap away. If we fail, we drop back to 1 pulse/sec and continue for a more realistic test. Testing at 20 pulses/sec is overly harsh, but it quickly uncovers any soft spots.

Next, we make our direct-contact tests. We discharge to exposed metal surfaces (including keyboards, indicators, connectors, and controls) in the relay-controlled direct-contact mode. For these tests, we usually hit each test point 20 times at about 1-sec intervals. The IEC 801.2 tests specify 10 shots/test point, so this gives us some margin.

Last, we make our direct-air-discharge tests. We try to discharge to nonmetallic areas, with an emphasis on keyboards and enclosure seams. If we are able to draw an arc, we hit those points 20 times at about 1-sec intervals, as with the direct-contact tests.

In all of the above cases, we start each test sequence at 2000V and test both polarities, positive and negative. Then we advance in 2000V increments (both polarities) until we either fail or reach the desired test-voltage limit. It's very important to test at all voltage intervals, not just at the peak levels because it's not unusual for a unit to fail ESD at 6 or 8 kV and pass at 10 or 12 kV.

Although it can take several hours to go through the entire test sequence, if you pass all these tests, you'll have high confidence that you will pass your ESD-compliance test as well. If you fail, you can stop and try some of the fixes we discussed in the third chapter. One final caution: ESD testing results in strong transient electromagnetic fields so you may upset nearby computers or test equipment. We once upset another long-term test in progress, much to everyone's chagrin. Be sure to check with your nearby colleagues before you begin zapping.

RF prescreening

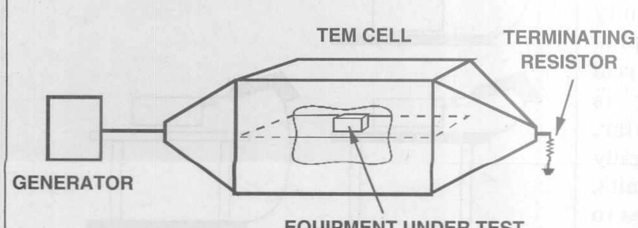
Due to equipment costs and test complexity, most of you will want to leave RF prescreening tests for the test laboratory. It can easily cost \$50,000 to \$100,000 for the equipment and facilities to do these tests. Furthermore, there can even be safety concerns at high RF-power levels.

For a quick and dirty test of RF immunity, we find it useful to momentarily key a handheld radio transmitter about 3 ft away from the equipment to be tested. At this distance, a 1 to 5W radio results in an electric-field strength of about 5 to 10V/m, depending on the antenna pattern and efficiency. If the unit fails this test, you know you are vulnerable to RF. If it passes, you still don't know anything because your system may be vulnerable at some other frequency, but at least you have a quick test you can perform.

An engineering manager for a company that designs medical devices would subject all prototype designs to his "CB-ham-radio" test. He would key a handheld CB radio (typically 2 to 3W at 27 MHz), plus assorted handheld ham radios (typically 1 to 3W at 145, 220, and 450 MHz) a few feet from a unit to see what happened. If there were any upsets, it was back to the drawing board for his designers. Needless to say, most of their designs looked pretty good by the time they made it to the lab for qualification testing.

If you work with physically small systems, you might want to consider purchasing a transverse electromagnetic (TEM) cell, as shown in **Fig 4.** This test fixture is essentially an expanded length of coaxial cable that provides a uniform electric field at moderate power levels. The cell is also shielded, so you don't need a special shield room to use it. The disadvantage is the relatively small size of the samples that can be tested, which must be less than about one-third of the volume of the cell. All TEM cells also have an upper frequency limit when they no longer work in the transverse-electromagnetic mode.

Fig 4—TEM cell for radiated immunity testing



Power-disturbance prescreening

Many designers prefer to leave power-disturbance prescreening tests for the test laboratory as well. They can be a bit complicated, and there are safety concerns due to large transient levels and the fact that you are working with live ac-power lines.

For quick and dirty power-disturbance testing, we find it useful at times to plug an electric drill into the same power receptacle and then repeatedly turn the drill on and off. Between the brush noise and the inductive kick from the motor, you can generate a fair amount of trash on the power line. As with the nearby radio transmitter, if you fail, you know you have a real problem.

If you do a lot of testing in this area, it may pay to invest in some power-disturbance testing equipment. Thanks to the European Community influence, new modular test equipment is rapidly becoming available to test for a wide range of power disturbances. KeyTek and Schaffner both recently introduced modular models to test for the electrically fast transient (EFT) of IEC 801.4, the surge (lightning) transient of IEC 801.5 and IEEE C63.41, and the anticipated sag/swell and dropout levels of IEC 801.6.

Audit testing

Audit tests are usually associated with manufacturing and quality, not design engineering. Nevertheless, you want to be sure that your design stays intact throughout its product life. We've seen several cases where manufacturing changes moved (or even completely removed) EMI or ESD protec-

tive devices, leaving the design completely vulnerable to a wide range of problems.

Thus, it's prudent to include some EMI audit tests as part of your overall EMI-design philosophy. These can include statistical checks, perhaps pulling an occasional unit off the production line and running it through a battery of EMI tests. If you have demanding EMI requirements, you might want to include simple screening tests on all production units. We've had several clients do screening tests for ESD and RF emissions where both caused serious operational problems. The screening tests prevented faulty units from making it into the field.

The real challenge with audit tests is keeping them simple (and inexpensive) and yet making sure that high EMI quality is maintained. You, as a designer, need to decide how important consistent EMI quality is in your designs and then how to best implement an audit-test program. EDN

That's it for some insights on EMI testing. We hope this chapter helped you understand different aspects of EMI testing and perhaps even gave you some ideas on how to endure this necessary evil. In the next and final chapter, we'll look at troubleshooting EMI problems in the field.

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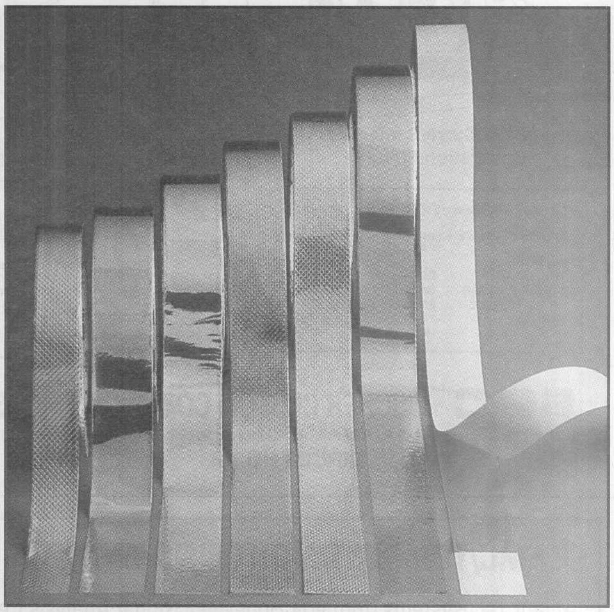
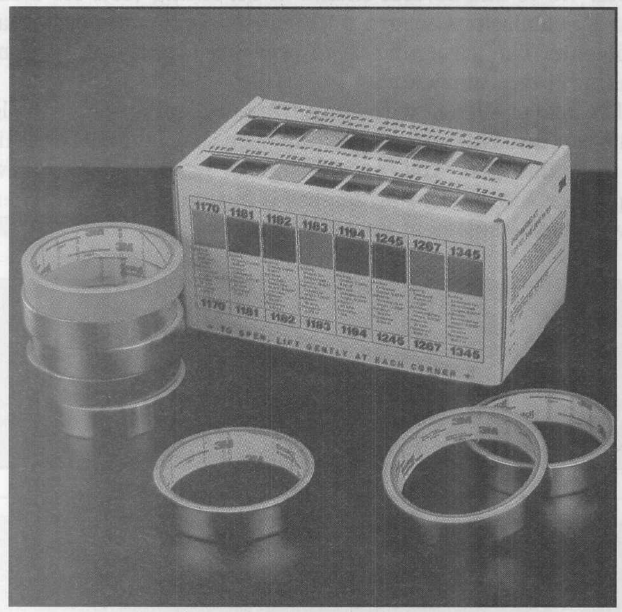


Scotch Brand Foil Shielding Tapes.



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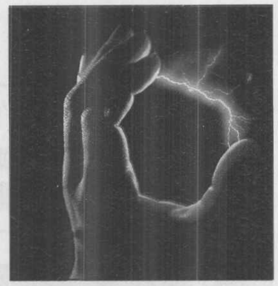


Troubleshooting… EMI in the trenches

It's late Friday afternoon, and you're winding down and looking forward to the weekend. Then the phone call comes—a production line is down because of EMI problems, and your attention is needed right away. Later that evening, you're on a plane wondering what you will find and what to do about it. You may even be wondering why you took this job in the first place. Whatever happened to just designing equipment?

No, this isn't science fiction. As EMI consulting engineers, we face this type of panic situation several times a year. In fact, as this is being written, we're waiting to hear whether one of us will spend the weekend at a manufacturing plant in North Dakota. An urgent call came this morning, and it's now Friday afternoon. Wait, the phone just rang…

All of our previous chapters have been aimed at solving or preventing EMI problems in the design stage. Sooner or later, you may be called upon to help solve an EMI problem in the field. In this article, we'll give you some insights on how to solve EMI problems while under fire.

Some EMI troubleshooting philosophy

In the very first chapter, we referred to Bob Pease and his series in *EDN* on troubleshooting analog circuits. Actually, Bob's wonderful and witty advice applies equally well to all types of electronic equipment—analog, digital, relay, motors, and more. We particularly liked his pearls of wisdom, such as "record the amount of funny" and "even things that can't go wrong, do." Bob stresses that effective troubleshooting depends on how you think about the problem as much as what you end up actually doing. We agree, and here are some of our thoughts on how to think about EMI troubleshooting.

Adopt an emergency-room mentality. We've used the medical-doctor analogy before in this guide, but even doctors have different approaches for different situations. In the emergency room, quick professional action is mandatory. So it is with many field EMI problems. You need to respond quickly, and you need to begin assessing the situation right away. You won't have all the information you'd like, and the situation may be tense and confusing. In really bad situations, you may even have participants shouting or screaming at you. Keep cool. You need to focus on the problem, not the emotions or personalities.

Diagnose first, then try fixes. Too often, we see cases where fixes are tried before anyone has even thought about the problem. If your doctor gave you a prescription before even listening to your symptoms, you'd find another doctor right away. The same is true with EMI problems. Even if everyone is demanding immediate action, you need to take time to gather information so you can make a preliminary diagnosis. Then you can try some fixes.

If at first you don't succeed, try again, as the old saying goes. Don't panic if your first fix doesn't work. Most of ours don't work the first time either. Remember, if the problem were simple, it likely would have been solved long ago, and you would not have been called in to help. While EMI miracles do occur (we each see about one miracle a year), most EMI problems are solved through old-fashioned hard work. A bit of luck doesn't hurt either. Here are some ideas and suggestions on how to attack EMI problems in the field.

Gather the information

Information is vital in dealing with EMI problems, but you need to know what questions to ask, and you need to organize your data. Finally, you need to know when to be skeptical and when to keep on digging for information.

Gathering the information is a bit like working a jigsaw puzzle. You need to get as many pieces as you can on the table, and then you start looking for patterns that fit together. At first, it

Diagnose first, then try fixes. Too often fixes are tried before anyone has even thought about the problem.

The Designer's Guide to Electromagnetic Compatibility

The country-doctor approach

One of us had a relative who was a country doctor in the first half of this century. We once had a chance to see the tools of his trade and were touched by their simplicity. The old black leather bag didn't hold a lot (a stethoscope, a thermometer, some simple surgical tools, and a few medicines), but when these few tools were combined with medical knowledge and experience, many lives were saved. It didn't take CAT scans and NMR systems to diagnose and solve a lot of problems. Sure, the latest technology is great, but you don't need it for every situation.

We like to remember that country doctor when we are troubleshooting EMI problems. Using a few simple tools (such as ferrites, copper tape, and aluminum foil), we've found that we don't need a million dollars worth of test equipment or reams of test data for many EMI problems. Like the country doctor, we can solve a lot of EMI problems by relying on our own experience, knowledge, and common sense. You can, too, if you just remember to think like that country doctor.

can be confusing and even frustrating, but as you proceed, the pieces of the puzzle start to fall into place. Even so, there will be vital pieces that are missing, but you can't let that stop you. If you are stumped in one area, go work on another. Often, you'll find a missing piece of information where you least expect it.

When working any puzzle, it helps if you have a strategy. With a jigsaw puzzle, it helps if you start with the corners and borders. Once that framework is in place, most of us look for blocks of pieces that seem to belong together. Pretty soon, we've put several pieces of the puzzle together, and then these larger blocks fit together as well. The picture start to emerge, and what was once a hodgepodge of pieces now starts to make sense.

When dealing with the EMI jigsaw puzzle, we start by asking four key questions:

- What are the symptoms? (equipment issues)
- What are the likely causes? (environmental issues)
- What are the constraints? (systems issues)
- How will we know when it's fixed? (success issues)

You can use these four questions as the four corner pieces to the EMI puzzle. You first need some preliminary answers before you start to dig deeper into the problem.

The symptoms deal with equipment issues. At this point, you're looking for general information, and your focus is inside the equipment. You don't need to know the minute details or the precise failure mechanism; you'll have time to dig into that later on. Right now, you want to gather as many symptoms as possible so keep the questions simple and direct. Think like a doctor, and ask the technical equivalents of: "Where does it hurt? When did you first notice it? Does it hurt when you do this or that? What else seems to be wrong?"

The likely causes deal with environmental issues. Now it's time to focus outside the equipment as you look for potential EMI suspects. We usually begin with three very common suspects: ESD, RFI, and power disturbances. We then ask questions about getting zapped (ESD), flickering lights or thunderstorms (power), and handheld radios or even nearby airports (RFI). If the problem is long term, there may even be seasonal clues. For example, summer upsets are often caused by air-conditioning-induced power glitches, while winter upsets are often related to ESD because winter's low humidity encourages static buildup. If the problem occurs only at night, check to see if the night watchman uses a handheld VHF radio. (We've seen that happen several times.)

Constraints deal with systems issues that are often cost related. These include both component and failure costs. Failure costs are particularly important because field failures often cost thousands of dollars, so trying to save a few dollars in components is often a very poor economic move. (You may be told that you can't add any costs, but most of the time, that is just wishful thinking.) Other constraints may include no internal modifications to circuits or circuit boards, which means you'll need to concentrate on cables, shielding, and filtering to block the EMI energy.

Finally, it's very important to determine what constitutes success. In some cases, you can define a specific criterion, such as passing ESD at 12 kV or being able to operate with the night watchman's handheld radio operating 1 ft from the equipment. Other times, criteria may be more abstract, such as "no failures for six weeks" or perhaps even just a decrease in nuisance failures or alarms. The success criterion is subject to negotiation and may even change as you work on the problem. Nevertheless, you should have a specific goal in mind and a method of determining if you have reached that goal.

Organizing the information

As you gather information, you need a way to organize it. In the first chapter, we wrote about developing a diagnostic framework, or skeleton, on which you can hang all the data you have gathered. This not only helps you keep things organized, but also shows you where you lack data.

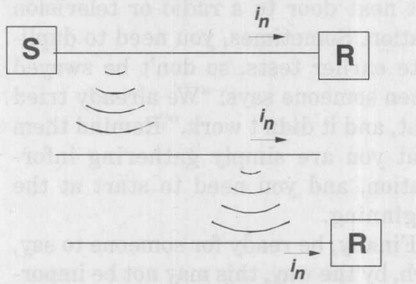
We use a simple organizational model, known as the source-path-receptor model. This model identifies the three critical elements for any EMI problem. All three must be present for an EMI problem to occur. If you can eliminate any one of these three, you no longer have an EMI problem. Sometimes, you can readily identify all three, and other times, you can only speculate. Nevertheless, this simple model can be a very useful tool to help

Fig 1—Source-path-receptor model

Any interference problem can be broken down into
- the SOURCE of interference
- the RECEPTOR of interference
- the PATH coupling the source to the receptor

Sources	Paths	Receptors
Microcontroller • analog • digital ESD Communications • transmitters Power disturbances Lightning	Radiated • EM fields • crosstalk capacitive inductive Conducted • signal • power • ground	Microcontroller • analog • digital Communications • receivers Other electronic systems

Fig 2—Coupling-mode transformations



COMMON COUPLING EFFECTS
- f<30MHz—CONDUCTED
- 30 MHz<f<300 MHz—CABLE RADIATION
- f>300 MHz—SLOT AND BOARD RADIATION

you organize and solve EMI problems. **Fig 1** shows this model once again.

Most of the time when you are dealing with field problems, you are constrained to working with the coupling path. Note that the path can be conducted or radiated and that transformations (conducted-to-radiated, radiated-to-radiated) can occur as shown in **Fig 2.** In addition, there may be more than one path, so, until you block them all, you still have a problem. We liken these multiple paths to a boat with a leaky hull. You can have many leaks (some large and some small), but you won't have a dry boat until you plug every leak.

Although a good starting point, the source-path-receptor model is still often inadequate. We like to gather additional information on five parameters, the FATID we also discussed in Chapter 1. FATID stands for frequency, amplitude, time, impedance, and dimensions. We like to determine as much as we can about each of these parameters as they relate to the potential sources, paths, and receptors. We look for high-amplitude sources coupled with low-level receptors, and we look for similar impedances, similar frequency ranges, and dimensions typically greater than $^1/_{20}$ of a wavelength.

Be sure to use the EFFT to move between time and frequency. The formula is simple ($f=1/(\pi\times\text{rise time})$), which means a pulse with a 1-nsec rise time or transient behaves about like a 300-MHz sine wave as far as coupling, shielding, and filtering are concerned.

Think like Columbo

We've always figured that Columbo, the well-known television detective, would be good at EMI troubleshooting. After all, solving EMI problems is a bit like solving crimes. There is a culprit and a victim, and the evidence is often scanty and incomplete. There may even be reluctant witnesses, particularly if someone is afraid of being exposed by a poor design.

We like Columbo because he lives in the real world. Unlike the legendary Sherlock Holmes who immediately focuses in on the key issue and makes everyone else feel like an idiot ("Elementary, my dear Watson"), Columbo bumbles along like the rest of us, trying to sort out fact from fiction.

But Columbo does have his methods and techniques, which we can adopt for EMI troubleshooting. Here's how you can think like Columbo. (The trench coat and cigar are optional.)

First, ask questions and then ask them again. What's really important here is to get everyone thinking about the problem and all the possible clues. Seek clarification on answers to the questions. Nothing is too insignificant at this point, so dig in and keep asking questions, even it the answers seem obvious. Often, the answer is not what you expected, and you've uncovered another important clue. Like Columbo, you should jot down notes as you go along.

Second, make a visual inspection of the crime scene. Are the cables and connectors good? Are there pigtails on cables or grounds? Are there unclosed seams or openings in the cabinets? Are internal cables placed to minimize coupling? Are power filters near the entrances, and are they properly grounded? How is the grounding in general? Is there anything that just seems "funny?" Make sketches, and take pictures, if necessary. We find a camera to be very useful here.

Be sure to check out the neighbors, as well. Is there a radio antenna or a microwave relay station nearby? We've seen highrises that are right in line with microwave paths. The microwaves can wreak havoc with the equipment in the building. What kind of equipment is used next door or in the floor above or below you? High-power units, such as welders or RF heaters can wreak havoc with nearby electronic equipment. Where are the elevators, and where are the building wiring and service equipment located? We've seen equipment upset by transients or magnetic fields from these sources.

Third, don't assume anything, and verify everything. Don't assume the power is clean just because the location is using a UPS. Don't assume you don't

have ESD problems because no one gets an ESD shock. Don't assume you don't have RF problems because you're not next door to a radio or television station. Sometimes, you need to duplicate earlier tests, so don't be swayed when someone says: "We already tried that, and it didn't work." Remind them that you are simply gathering information, and you need to start at the beginning.

Finally, be ready for someone to say, "Oh, by the way, this may not be important, but..." Often, this tidbit of information is the gem you've been seeking. When we are troubleshooting, we actively solicit the "Oh, by the way" comments. You should, too.

Making a diagnosis

Now that you've gathered the information, you're ready to make a preliminary diagnosis. You may revise this diagnosis as you progress, and you may even be dead wrong. Nevertheless, you need to start with a diagnosis so that you can prescribe a course of action. Here are some thoughts on the diagnostic process given to us by some medical doctors.

First, rule out the least likely causes of the problem. This procedure may take several steps as you go through a thought process, known to medical doctors as differential diagnosis. In this case, you are moving from the general to the specific as you try to match the symptoms to the disease. For example, a red rash may suggest measles, chicken pox, or even bubonic plague. But if bubonic plague is also accompanied with a hacking cough and you don't have a cough, then you can eliminate bubonic plague as a likely source. Then you decide what is unique to either the measles or chicken pox, and continue the process of elimination. In some cases, you may still be left with several possibilities, but at least you have narrowed the list of candidates.

Fig 3—Troubleshooting radiated emissions

- Start with the lower frequencies and work up
- Attack cables first—they are the worst offenders
  - Move them while standing away from the antennas
  - Hot cables exhibit significant emission changes with differing cable positions
  - Current probe may help
  - Determine which cables are hot; there will commonly be more than one
  - Clamp ferrites on cables to suppress above 30 MHz
  - Inspect for possible leakage paths at or near cable connectors
- If emissions persist even when a cable is completely shielded and terminated, then look to the shield itself for leakage
  - High frequencies (150 MHz) will leak out seams
  - Ensure gasketing and fasteners are making contact by pressing on enclosure seams
  - Near-field probes may help to localize source
  - Seams may need to be stripped to get to conductive layer

Fig 4—Troubleshooting conducted emissions

- Conducted emissions can be isolated with the use of current probes
- Determine if emission is common or differential mode by probing singly or in combination
- If the emission is differential mode, the source probably originates as a signal, which needs to be filtered or shielded
- If the emission is common mode, the source is probably due to conducted or near-field coupling. Filtering will not solve problem, because it is common on the ground, but will respond to bulk ferrite

Next, decide what is the most likely of the remaining possibilities. We refer to this as the "rule of 90 and nine." To continue our medical example above, if a red rash is caused by the measles 90% of the time, then that is the cause to attack first. That way, you are right nine times out of 10. If your course of action doesn't work, then go with the alternative. Even then, that second course is often right only 90% of the remaining time, so you may need to go through the process again. Don't give up, but just keep trying. Like medicine, EMI troubleshooting is not an exact science.

Attacking the problem

After the diagnosis, it's time to write a prescription. That means you're ready to try some fixes. But don't just throw the fixes at the problem without thinking about the results. Rather, predict the results of a fix, and then try it.

If your prediction is right, keep going in that direction. Incidentally, if you are really lucky, that first prediction completely solves the problem. When this happens, try to act humble, because it won't happen very often. We each get lucky like that about once a year, and we do this for a living. The rest of the time, we just sweat it out (but we do guess right more often more than we used to). If your prediction is wrong (for example, the noise increases instead of decreases), don't despair. At least you are still getting a response to your fixes from the system. Remove the fix, and try something in another direction. Incidentally, this situation is quite common when dealing with grounding or cable-resonance problems.

If nothing happens when you install a fix, try another fix. Don't remove the first fix, however, as you may need several fixes to solve the problem. Remember our earlier example of the leaky boat with many holes in the hull. Many leaks require many fixes, not just one.

A common mistake we see is being too "scientific" at this phase of the troubleshooting by trying only one variable

Fig 5—Troubleshooting radiated susceptibility

- Radiated susceptibility troubleshooting is similar to radiated emissions
- First, move cables to determine which, if any, are sensitive to radiated energy
- Sensitive cables should be tied off to enclosure to shunt energy, or try bulk ferrites
- If possible, localize by removing cables, one by one
- ESD testing is good for injecting faults into digital circuits
- RF testing is better for analog circuits but may also work for digital circuits

Fig 6—Troubleshooting conducted susceptibility

- Conducted susceptibilty is generally due to inadequate filtering or improper filter termination
- Ensure that filters are tied off to case, not to circuit ground
- If problem is at high frequencies (or EFT), a commercial power-line filter may be inadequate. Supplement with high-frequency filters, such as ferrites

at a time. Another mistake is not trying fixes that are not "practical," meaning that they might be difficult or expensive to implement. Don't fall into those traps. At this point in the troubleshooting process, you want to know if the problem can even be solved. This is the time for bold moves, not caution or precision. If you solve the problem, you can always go back and remove parts or optimize the solution.

In addition to adding fixes, be prepared to subtract things as well. The isolation of EMI problems is a often a process of elimination. Eliminate as many variables as possible by removing cables or equipment or by powering down parts of a system, and then observe the results. We have occasionally solved EMI problems by removing parts. No, it doesn't happen often, but you'll never know if you don't try. At a minimum, you may narrow the range of EMI suspects by removing things.

Finally, we've included some specific tips on EMI troubleshooting in **Figs 3** through **6.** We've arranged these tips by the type of problem you are facing, using the MIL-STD-461 model of radiated emissions, conducted emissions, radiated susceptibility, and conducted susceptibility.

Some useful test equipment

As we stressed in the previous chapter on EMI testing, you don't need $1 million worth of equipment to get good EMI engineering data. This is also true with EMI troubleshooting. In fact, you can often obtain a lot of useful data with simple and inexpensive tools. The secret is knowing what you are looking for and paying attention to the results.

The first class of equipment includes monitors, equipment that lets you see what is going on in the equipment and the environment. Here are some we find useful:

Power-line monitors: Useful when you suspect power disturbances. Available in single- or 3-phase systems and designed to be left in place for days, weeks, or even months, they can be set to trigger and record data on a wide range of power disturbances. They are limited to about a 2-MHz bandwidth, so they miss fast transients. We usually rent these for cases of on-site troubleshooting. You might consider purchasing a power monitor if you have multiple customer sites to support.

Oscilloscopes: Useful for looking at time domain problems, such as fast transients or digital signals. Storage scopes are useful for transients, but they must be fast enough to capture 1-shot events. Remember that you need 100 MHz to view 3-nsec rise times and 300 MHz to view 1-nsec rise times. Portable, battery-operated scopes are useful for isolating power problems, particularly for fast transients and high-frequency noise that a power-line monitor might miss.

Spectrum analyzers: Useful for looking at frequency-domain problems, such as threats from nearby radio or radar transmitters. A frequency range of 10 kHz to 1 GHz is adequate for most EMI troubleshooting unless you suspect radar transmitters. You'll need to go to at least 18 GHz or perhaps even higher to fight radar-induced problems. You'll need suitable antennas as well.

Field-intensity meters: Useful for screening for high levels of RF or magnetic fields. These devices do not give you frequency information, but they are portable and very easy to use.

ESD charge meter: Useful to screen for ESD problems. These devices detect the presence of electrostatic charges and are particularly useful when you are trying to isolate equipment-generated ESD.

Your eyes, ears, hands, and even your nose: Use your senses to observe what is going on in the environment. Look around you, and listen to what is being said. Pick up the equipment, wiggle the cables, and poke around inside. And yes, take a whiff of it. We all know what a hot or burnt component smells like.

The second class of useful equipment is "failure forcers." These can be particularly useful when dealing with intermittent problems. Once you can force a failure to occur, it is much easier to diagnose and fix that problem.

ESD gun: Useful for forcing ESD events. We often use a small portable ESD gun when troubleshooting suspected ESD problems. This tool can also help find shielding leaks in cabinets and can identify cables that are very susceptible to RF and ESD pickup. Watch out, though; ESD can cause damage, so start with low levels. On the other hand, if the ESD gun does

cause damage, that same equipment is likely vulnerable to real ESD in the environment.

Handheld radio transmitter: Useful for forcing RF upsets. We often use a small portable CB radio when troubleshooting suspected RF problems. If we are in a facility that uses VHF radios, we may borrow one of those and try keying the radio a few times near the equipment. Be courteous when doing this. You need only a few very brief transmissions to try this out.

Electric drill or similar power tool: Useful for forcing power disturbances. We often use an electric drill and turn it on and off rapidly. The drills generate a lot of high-frequency noise plus some lower frequency transients due to inductive spikes. In a facility, we may also cycle nearby equipment on and off to force its transients into the power system.

Finally, here are some parts that are useful in isolating EMI problems. When we go troubleshooting, most of these are in our bag of tricks.

Aluminum foil: Can provide excellent high-frequency shielding. It is very useful in identifying leaky enclosures and cables. We've been known to stop at grocery stores to purchase a roll or two of aluminum foil en route to a visit.

Conductive tape: Useful for temporary closure of seams and temporary ground paths. Be sure the conductive tape is designed for EMI and has a conductive adhesive. Most conductive tapes from hobby or art stores do not have conductive adhesives.

Bulk ferrites: Useful for clamping onto cables to suppress high-frequency common-mode current flow. Remember, ferrites work best at frequencies above 50 MHz. Most of the ferrite vendors have ferrite kits for cable suppression.

Power filters: Useful for installing in power lines. We have several power-line filters, ranging from single-phase filters of a few amps to 3-phase filters of about 30A. Use care when installing these filters, as the wiring carries power-line currents and voltages.

Signal filters: Useful for installing in line with signal cables. These are available in popular configurations, such as for DB9 or DB25 connectors and can help quickly isolate high-frequency differential-mode problems on signal cables.

Assorted components: We also carry an assortment of components, including high-frequency ceramic capacitors (typically 0.001 to 0.1 μf), ferrites (beads, toroids, and beads on leads in various sizes), inductors (10-μH hash chokes), and resistors (10 to 50Ω for damping clock oscillations). We also include copper braid and stainless-steel hose clamps if we anticipate cable problems. EDN

That's it for EMI troubleshooting. We hope we've given you some insights into the process, as well as some concrete tips and techniques. We also hope that we have instilled a positive attitude and perhaps even a sense of excitement toward this important process. For although some designers view troubleshooting as part of testing, we disagree. We see EMI troubleshooting as a natural extension of the design process, using the designer's finely honed skills of dealing with new challenges in the face of uncertainty.

This also brings to a close our entire series on EMI for designers. We hope you've found it useful and perhaps even a bit enjoyable. It has been a lot of work for us—much more that we dreamed when we began working on this project over a year ago. But if this helps you, our design colleagues, build better products and make this a better world, then it's been worth it.

Please let us and the folks at *EDN* know how you liked it.

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